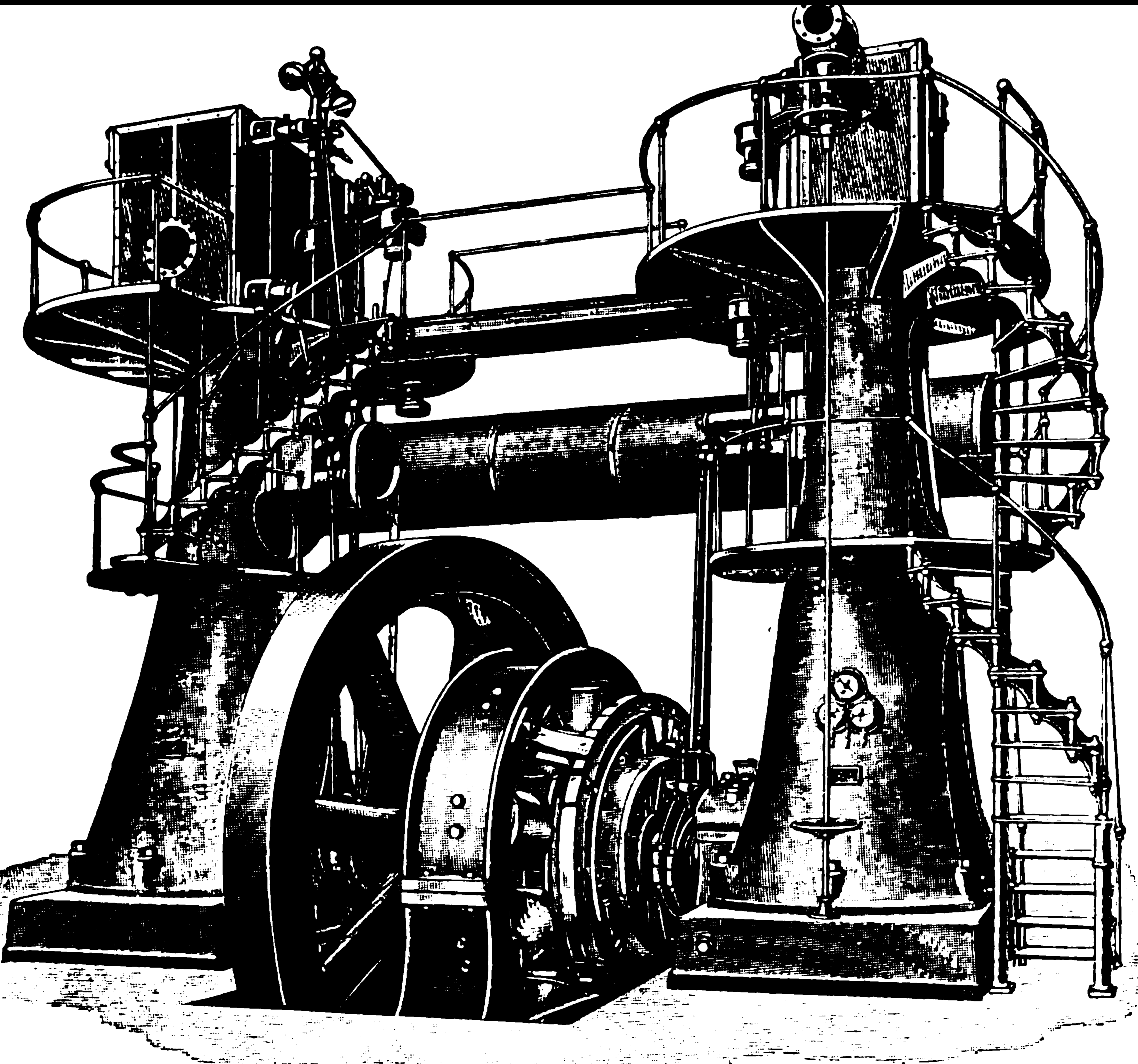

Electric Lighting

Francis Bacon Crocker

ELECTRIC LIGHTING

A

PRACTICAL EXPOSITION OF THE ART

FOR THE USE OF

ENGINEERS, STUDENTS, AND OTHERS INTERESTED IN
THE INSTALLATION OR OPERATION OF
ELECTRICAL PLANTS

VOLUME I.

THE GENERATING PLANT

BY

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PREFACE TO FIRST EDITION.

ELECTRIC LIGHTING having now become one of the most important branches of applied science, there is a demand for information on the subject. This demand is by no means confined to electrical engineers, but applies also to mechanical, mining, and other engineers, architects, fire underwriters, students in colleges and technical schools, lawyers and business men who may be called upon to consider questions relating to electric lighting. But the development of this art has been so very rapid, and so many changes and improvements were continually being made, that heretofore any attempt at a complete treatise on the subject would become out of date while it was being printed.

There are already good elementary works on electric lighting; and in the case of special branches, such as the dynamo, transformer, electrical distribution, etc., we have several excellent books; but none of these cover electric lighting as a whole, or what might be called electric-light engineering.

The author believes that the time has now arrived, however, when electric lighting has reached a sufficiently perfected and established state to allow of its being treated in a fairly satisfactory and permanent manner.

The plan adopted in this book is to follow the usual sequence in which the electric current is generated, transmitted, and utilized in electric lighting. That is to say, the introductory principles are first given; then the building, boilers, engines, dynamos, distributing conductors, lamps, etc., will be considered in the natural order in which the electrical energy is first obtained, and finally converted into light in the lamps. The attention of the reader is particularly called to this arrangement, which is given in full in the Table of Contents. This order not only facilitates the understanding and remembering of the various parts of the subject, but also enables one to quickly turn to any particular part without

using the Table of Contents or Index, since one knows without any effort of memory the position of each element with reference to the others.

The entire subject of electric lighting naturally divides itself into two parts; one relating to the generating-plant, and the other covering the distributing conductors, lamps, special applications, etc. The present volume is confined to the first part, the other subjects being given in Volume II.

In many courses of instruction the subject of steam- and gas-engines, water-wheels, and other purely mechanical matters, are not included in the lectures on electric lighting, being taught by other instructors as entirely distinct matters. In fact, the author approves of this plan himself; nevertheless, for completeness, it was deemed proper to incorporate the mechanical subjects with the electrical ones, and to consider particularly their application to electric lighting. These portions of the book will at least serve as a review or memorandum of what it is essential to know, even though the knowledge has already been acquired elsewhere.

It is quite a common fault in technical books that many of the machines and methods given as examples are either untried

The author desires to express indebtedness to his former pupils, Messrs. C. H. Parmley and Max Osterberg, whose carefully taken notes of his lectures formed the basis of this work; to Professor R. B. Owens of McGill University for ideas on the location of a station (Chapter V.); to Professors M. I. Pupin and F. R. Hutton, Mr. E. A. Darling and Mr. G. F. Sever of Columbia University for proofreading and suggestions in regard to the steam-engine, dynamo, etc. (Chapters VIII. to XVII.); also to Mr. Gano S. Dunn and Mr. D. R. Lovejoy for proofreading.

PREFACE TO SIXTH EDITION.

THE first edition of this book appeared in 1896, and four editions containing revisions have been published since. The present edition has been practically rewritten, bringing the various branches of the subject thoroughly up to date. The original arrangement of topics and the treatment of fundamental facts are retained, but the earlier types of apparatus have been replaced by the latest examples. Much new matter relating to recent developments in station design, steam-turbines, gas-engines, direct-connected generators, storage batteries, etc., has been introduced. Particular care has been exercised in eliminating the dead wood consisting of antiquated illustrations and statements, which are too often left in revised editions of technical works. This book has been used for eight years as a text-book in a number of engineering schools, and as a result of this experience the new edition is better adapted to its purpose. It is also intended as a handbook for engineers and architects, including those not specialists in electrical work but who desire to obtain information regarding it. "Electric Lighting" is retained as the title, but generating plants for railway, power, electrochemical, electrometallurgical and other purposes embody the same elements arranged in a similar manner, so that the book also applies to them. In a general treatise of moderate size it is impossible to cover this subject exhaustively, but the principle, construction, and action of each main or auxiliary piece of apparatus, also its relation to the others, is explained to an extent proportional to its importance.

In the preparation of the present revised edition, the author received much valuable assistance from his friends and colleagues Morton Arendt, E.E., Dr. C. E. Lucke, and Professor George F. Sever. The author also takes this opportunity to thank the various manufacturers and engineers who have kindly furnished information as well as illustrations.

CONTENTS.

ELECTRIC LIGHTING.

CHAPTER I.

INTRODUCTION.

Electric Lighting is the art of producing artificial illumination by means of electrical energy.

Generally speaking, an electric lighting system comprises three essential elements, viz.: —

1. *Apparatus for generating the electrical energy*, for which purpose dynamo-electric machines driven by steam or gas engines or water-wheels are almost universally employed.

2. *Means for transmitting and distributing the electrical energy*, which consist largely of copper conductors.

3. *Devices for converting the electrical energy into light*, which are practically always either arc or incandescent lamps.

In addition to these three essential elements, certain auxiliary devices are commonly employed, such as transformers, secondary batteries, switching, regulating, and measuring apparatus, etc.

The words *system*, *installation*, and *plant* are all used to designate the collection of apparatus and other elements employed for electric lighting in any given case. The first term is used too freely; as, for example, when some trifling device is called "a new system of electric lighting." Nevertheless, these terms have their legitimate use in discussing electric lighting. Their significance in this connection is substantially identical with their ordinary meaning.

The dynamo-electric machines used in electric lighting are the various well-known forms of mechanical generators of electricity. They may be defined as machines for converting mechanical energy into electrical energy; or, in other words, they generate electric currents when driven by mechanical power.

The term dynamo-electric machine is so long that it is usually and almost unavoidably shortened into "dynamo," which

has exactly the same meaning. The name "electric generator," or simply "generator," is often applied to the dynamo, especially when it is used to produce current for electric railway or other motors; but this distinction is merely for convenience. An alternating current dynamo is commonly called an "alternator."

Two essentially different kinds of electric currents are in use, *direct* and *alternating;* and the differences between them give rise to very important variations in the construction and operation of electric-lighting plants.

A direct or continuous current flows in one direction only; whereas an alternating current reverses its direction of flow, and usually the reversals occur very rapidly, that is, 50 to 266 times per second, the "frequency" or number of *complete periods* being between 25 and 133 per second in all systems in general use.

The steam or gas engines and water-wheels employed in electric lighting are practically the same as those used for other purposes, except that it is especially important that they should be very constant in speed.

Steam and gas engines and water-wheels being practically the only prime movers or sources of mechanical power used in electric lighting, are quite fully treated in Chapters VII. to XIV. inclusive.

The mechanical connection between the engine and dynamo is a matter of much consequence; in fact, it has been the cause of considerable trouble and discussion in electric-light engineering, and it therefore receives particular attention in Chapters XV. and XVI.

The dynamo being by far the most essential element in electrical engineering is treated in considerable detail. Chapter XVII. is devoted to the principles and construction of dynamos, Chapter XVIII. to typical forms, and Chapter XIX. to the practical management of these machines. The last subject is certainly of fundamental importance in electric lighting; and no fact concerning it, however small, is unworthy of consideration. Indeed, to nearly all electric-light engineers a knowledge of the construction of the dynamo is chiefly useful because it enables them to manage these machines more intelligently, and not because they are called upon to design or build them.

Accumulators are often used in connection with the generating-

plant. An accumulator, also called a secondary or storage battery, consists of a number of voltaic cells containing plates or electrodes and a conducting liquid or electrolyte. Such a battery is inert in itself; but, on passing a current through it, certain chemical changes are produced, which render it capable of afterwards reproducing a large fraction of the electrical energy put into it.

In Europe accumulators have been more extensively and successfully employed than in the United States, but they are now being quite rapidly introduced into central stations and isolated plants in this country.

The principles, construction, and action of accumulators are discussed in Chapter XX.; and their use in electric lighting is considered in Chapter XXI.

Switchboards, including measuring instruments, switches, circuit-breakers, fuses, automatic cut-outs, rheostats, ground detectors, and other similar apparatus, are described in Chapters XXII. and XXIII.

Lightning arresters, which involve almost the only very uncertain questions in electric lighting, are carefully considered in Chapter XXIV.

This completes the list of elements which form part of the generating-plant; and the remainder of the subject, comprising the distribution and utilization of the electrical energy, is treated in Volume II. The subjects therein discussed include the principles, methods, and apparatus employed in direct- as well as in alternating-current distribution, underground and overhead conductors, recording-meters, house-wiring, arc and incandescent lamps. It will be noted in both volumes that the order in which the various subjects are treated follows the usual sequence of generating, transmitting, and utilizing the electrical energy for lighting or other purposes. This being the natural order is easier to follow than any arbitrary arrangement.

ADVANTAGES AND DISADVANTAGES OF THE ELECTRIC LIGHT.

Before entering upon the detailed study of electric lighting, certain general questions present themselves for consideration. In the first place, the relation of the electric light to other forms

of artificial light is a matter upon which its ultimate success or failure necessarily depends. In other words, if the electric light does not possess decided advantages over the gas light and other means of lighting already in existence, it is obvious that its introduction is of no utility, and the study of it is unnecessary. In short, the very existence of the electric light in practical use depends upon its exact value compared with that of its rivals; and therefore it will be well to carefully consider its various advantages and disadvantages.

The marked advantages of electric light over gas light may be enumerated as follows:—

1. It does not vitiate the atmosphere;* that is, it neither consumes the oxygen upon which the life and health of human beings depend, nor produces carbonic acid or other gases which are deleterious.

2. It is much cooler; i.e., it produces less than one-tenth as much heat for the same amount of light.

3. It can be lighted without the aid of matches, which is not only a great convenience, but also largely reduces the danger of fire.

4. The incandescent light is much steadier than gas light, and does not flicker even in a strong current of air.

5. The incandescent lamp itself is practically free from the possibility of setting fire to anything, because the source of light is hermetically sealed in a glass globe; and even if the globe is broken in a barrel of gunpowder or kerosene, it will not ignite them.†

6. The lamps are capable of much more convenient and æsthetic arrangement; that is to say, lamps can be put close against a wall or ceiling, or they can be placed pointing upward or downward, or inclined at any angle, all of which arrangements are impossible in the case of gas or other kinds of lamps.

7. The lamps can be lighted and controlled from any desired point, such as the entrance to a building or room.

* This is strictly true only of the incandescent lamp, but it practically applies to the arc lamp also.

† A mixture of explosive gases, however, might be exploded in this way. But this danger is largely avoided by enclosing the lamp in a thick glass globe. If a lamp is in contact with or enclosed in cloth, wood or other combustible material, the heat may accumulate sufficiently to char or set fire to the latter.

8. Incandescent lamps can be obtained of any power, from a small fraction of one candle-power up to several hundred, and one can be substituted for the other in a few seconds, which is not practicable with any other means of illumination.

It should be remarked that the above advantages apply more particularly to the incandescent electric light than to the arc light; but the former is the one used almost entirely for interior illumination, the latter being used more for street lighting and other rougher uses, where fine points of advantage are not of so much consequence.

The only disadvantages of the electric light to offset the numerous and important advantages stated above are:—

1. The electric light cannot be turned down like a gas or oil lamp.

This objection is often urged; but it amounts to very little, because it is rarely desirable to turn down a light, and ninety-nine times out of a hundred when it is done it is to save the trouble of relighting. To avoid danger of fire, and for other reasons, it is ordinarily a positive advantage to turn out a light entirely when not required; and this can be done in the case of the electric light without involving any trouble in relighting it.

Furthermore, the incandescent light can be dimmed, if desired, in several ways. A resistance can be used for a direct current, and a choke coil for an alternating current; and either of these can be applied without much trouble or expense, and the only reason they are not often used is that they are not needed. For a sick-room, or other place where a dim light is required, a low candle-power lamp can be employed, or the light can be shut off by a shade or screen.

2. It is often stated that the electric light has an injurious effect upon the eye. The intense glare and usual unsteadiness of an arc light are often unpleasant, and would probably be harmful to the eye if exposed to it for any length of time. But the arc lamp is generally used for lighting streets, halls, railway stations, and other places where sight is general, and not applied to small objects. For lighting small spaces, or for any case where reading, writing, or other fine work has to be done, the arc light should be shaded, or arranged so as not to throw its glare directly into the eye.

The incandescent light seems to be steadier than any other kind of light; but the author has heard of, or actually observed, cases where sensitive eyes were disagreeably affected by it. The slight fluctuations in speed and current due to the strokes of the engine often produce a perceptible flickering in the lights, which can best be detected by observing a piece of white paper held near the lamp. This may be overcome or reduced by higher speed or heavier fly-wheels, and certainly should be brought down until it is imperceptible. Two or more engines or dynamos working on the same circuit might shift the load from one to the other, or otherwise act inharmoniously. This would be more likely to occur with alternating currents which might surge back and forth, due to lack of perfect synchronism or equality of action in the generators. The sudden throwing on or off of motors or a considerable number of lamps, the intermittent slipping of a belt or inductive action between two or more alternating currents differing slightly in phase, are also causes of variation in lamps which should be guarded against.

3. The incandescent light is sometimes more expensive than gas light; but in isolated plants in hotels, factories, etc., where boilers, engines, and engineers are required in any case, the *extra* expense due to the electric light is small, and it costs less than the equivalent gas. When the exhaust steam is used for heating, the introduction of electrical generating machinery adds little to the coal consumption. With the arc, Nernst and Hewitt lamps, which require less watts per candle-power than the ordinary incandescent type, the cost of electric lighting is still lower.

As a matter of fact, however, the real importance and utility of the electric light is dependent upon its radical advantages over any other form of artificial light; and whether it costs a little more, a little less than, or exactly the same as, gas light, is not so very important. For example, gas light costs more than lighting by kerosene lamps; but the greater convenience and general superiority of gas are sufficient to practically eliminate the use of kerosene wherever gas is available. The advantages of the electric light over gas are similar in character to, and fully as great in degree as, the advantages of gas over oil; and this applies to the Welsbach burner and acetylene gas as well as to ordinary illuminating-gas. The advantages of the incandescent lamp

stated above, particularly the facts that it does not vitiate the atmosphere or produce as much heat, and can be lighted without matches, make it a superior kind of light in practically every respect; and it is probably a fact in nearly every case where electric light is introduced instead of gas, that this is the reason, and not because it is expected to be cheaper than gas. This, however, is only true when the cost of electric light is approximately equal to that of gas. If the cost were very much greater, it would prevent its use in many cases. If, on the other hand, electric light is actually cheaper than gas, in addition to its other decided advantages, then there would appear to be no reason why it should not be used almost universally wherever it can be obtained.

The standard incandescent lamp (carbon filament), giving 16 candle-power, consumes about 50 watts, and the ordinary charge for current to supply it is about three-quarters of a cent per hour. This applies to small quantities obtained from electric-light companies. For larger quantities a discount is generally made, and when a customer uses several hundred thousand kilowatt-hours per year the price may be one-half cent or less per lamp-hour. In most cases electric power for running motors is sold at a lower rate than for lighting because the former service usually extends over longer periods of time. The machinery in a factory, for example, runs about ten hours a day, whereas the lamps may be in use only an hour or two in winter and not at all in summer. On account of this difference a common charge for electric power is about five cents per K.W.-hour even for moderate quantities and corresponds to one-quarter of a cent for a 50-watt lamp. Large water-power plants under favorable circumstances are able to sell electrical energy at very low rates. At Niagara Falls the charge is about .015 cent per lamp-hour (50 watts), and about $20 per horse-power-year for twenty-four hours a day, which is less than one-third of a cent per K.W.-hour.

In isolated plants (steam), for the reasons stated on page 6, the cost of electric light or power is often less than the charges of electric-light companies. Fairly large installations properly designed and operated produce electrical energy at about 4 cents per K.W.-hour

CHAPTER II.

HISTORY OF ELECTRIC LIGHTING.

LIGHTNING is the first and grandest form of electric light. Ordinarily, however, we confine the term to mean artificial electric light. Considered from this point of view, probably the first electric illuminating effects obtained by man were electric sparks produced intentionally or accidentally by frictional electricity. The effects obtained, however, in these very early experiments were so feeble that they are hardly worth considering; and it was not until the first electrical *machine* was made by Otto von Guericke, about the middle of the seventeenth century, that the sparks produced were sufficiently powerful and frequent to be looked upon as even the germ of the electric light. In fact, the duration of an electric spark being only an almost infinitesimal fraction of a second, it can hardly be considered to be a light of any practical use. Later, however, the frictional electric machine was improved by Newton and others, and numerous experimenters took up the study and development of electricity. One line of work which probably produced an electric light worthy of the name earlier than any other method, and one which has recently assumed particular importance, is the production of light by means of electrical *discharges* in air or other gases, whether rarefied or not. Intermittent electric sparks are entirely too sudden and temporary, unless the number of sparks is made sufficiently great to be practically equivalent to a continuous discharge.

During the latter part of the seventeenth and early in the eighteenth century numerous experiments were made with discharges in air or rarefied gas.

The record of these may be found in a book entitled *Physico-Mechanical Experiments on Various Subjects, containing an Account of Several Surprising Phenomena touching Light and Electricity.* By F. Hauksbee, F.R.S. Published in London in 1709.

The above experiments deserve to be considered as being the first production of the electric light in anything like a practical

way, although heretofore they have been ignored so far as the history of electric lighting is concerned; but the interesting experiments of Tesla and others in connection with electrical discharges might lead us to look upon these very early attempts as being as important as much later experiments which are ordinarily given as the origin of the electric light. Leaving aside, however, the question of what the electric light of the future may be, it is certainly a fact that the electric light of the present day depends essentially upon the use of an electric *current* of several amperes, or a large fraction of one ampere. Frictional electric machines cannot give any such current; therefore electric lighting of the kind now practiced was an impossibility until some source of electric current was discovered. The first source of this kind was the primary battery, or chemical generator of electricity, invented by Volta in 1800. The voltaic battery was soon taken up and developed by scientific men, and batteries of sufficient power to produce quite strong currents were made by Volta himself and by others. Sir Humphry Davy immediately recognized the great possibilities of the battery for scientific and practical use, and constructed a very large one of 2,000 pairs of plates in 1808. This battery was used by him in various investigations; and in the years of 1809 and 1810 he performed with it the epoch-making experiment of producing a continuous and brilliant electric light, which was practically identical in principle with the arc light of to-day. This experiment is best described in his own words as follows: "When pieces of charcoal about an inch long and one-sixth of an inch in diameter were brought near each other, within a thirtieth or fortieth part of an inch, a bright spark was produced, and more than half the volume of charcoal became ignited to whiteness; and by withdrawing the points from each other a constant discharge took place through the heated air, in a space equal to at least four inches, producing a most brilliant ascending arch of light."

It should be noted that in the above experiment Davy made use of *carbon* electrodes, which are the essential elements of the present arc lamp; and carbon is also used for the filament of all practical forms of incandescent lamp. He also noticed the arched form of the electric current between the carbon points, from which form the arc derives its name. This great experiment is unques-

tionably the foundation of the present methods of electric lighting; but the use of a voltaic battery as the source of current prevented any extensive introduction of the electric light, on account of the prohibitive expense and trouble of running a battery large enough to give sufficient current. A much more powerful and cheaper source of electrical energy was needed to make the electric light a practical success; therefore little or no progress was made until the discovery by Faraday, in 1831,* of magneto-electric induction, which was almost immediately followed by the rapid development of the magneto-electric machine, or mechanical generator of electricity, from which has been evolved the modern dynamo-electric machine. The most notable of the first machines were those of Dal Negro,† Pixii,‡ Saxton (1833),§ and Clarke (1835).‖ These machines were all similar in principle, and consisted essentially of coils or bobbins of copper wire and a permanent magnet, one of which was revolved and the other held stationary. This rotation produced primarily an alternating current in the coils, which was led out by suitable connections. At the suggestion of Ampère,** a commutator was added, in order to obtain a direct current; that is, one flowing in one direction only. These magneto machines were perfected and built on a larger scale by other experimenters.

The most noteworthy types of these larger machines were the "Alliance machine" and the "Wilde machine." These forms were made of considerable power; that is to say, they were capable of generating currents of several horse-power, and adapted to being used for practical work. The Alliance machine originated with Nollet in 1849, and was improved by Holmes, Masson, Du Moncel, and others; and in 1857 it had been brought up to a fairly perfected condition. In 1863 this machine was applied to lighting the lighthouses of the French coast by electricity. This was probably the first important *practical* use of the electric light, and is therefore of great interest. About the same time the Wilde machines were also being used to generate current for arc lights; but these for the most part were for experimental or exhibition purposes. These machines, it should be

* *Experimental Researches*, vol. i. p. 25. † *Phil. Mag.*, July, 1832.
‡ *Ann. Chim. Phys.*, vol. l. p. 322, 1832. § *Phil. Mag.*, 1836. ‖ *Ibid.*
** *Ann. Chim. Phys.*, li., 76, 1832.

remembered, were up to that time of the magneto type; that is to say, the field magnetism was produced by permanent magnets. The use of electro-magnets, and the principle of self-excitation as applied to the modern dynamo-electric machine, was developed by various workers. In 1845 Wheatstone and Cooke patented the use of electro-magnets instead of permanent magnets, which were, however, to be excited by a current obtained from some source outside of the machine itself, being what is now called separately excited. Brett, in 1848, suggested that the permanent magnetism in a magneto machine might be increased by the current of the machine itself. Sinsteden independently made a similar suggestion in 1851. Wilde, in 1863, used a small magneto machine to supply currents to an electro-magnet which formed the field magnet of a very much larger generator. In this way he obtained very powerful effects, and made a machine capable, for example, of fusing a copper rod of considerable diameter. The definite and complete invention of the principle of using the current of the machine itself to feed its own field magnet was independently and almost simultaneously announced by Werner Siemens to the Berlin Academy on Jan. 17, 1867, and by Sir Charles Wheatstone to the Royal Society of London on Feb. 14, 1867. This gave to the world the modern dynamo-electric machine, upon which, more than anything else, the great success of electric lighting and almost all the other applications of electricity depends. The next important step in the development of the dynamo was the improvement of the armature, which up to that time had been quite crude. In 1860 Pacinotti designed, and in 1865 published* a description of, a machine having a ring armature with a continuous winding. This is the essential element of the very high efficiency direct-current generators of the present day. This invention was practically, ignored until it was independently rediscovered by Gramme in 1870.

The invention of Pacinotti had been merely a laboratory experiment, whereas Gramme took up the subject as an engineer, and designed and constructed many successful machines of this type. In 1873 von Hefner-Alteneck applied Gramme's principle of a continuous or closed-coil winding to the shuttle armature invented

* *Nuovo Cimento*, xix., 378, 1865.

by Werner Siemens in 1856. The Siemens shuttle armature, sometimes called the I armature on account of the form of cross section of its iron core, was at the time of its invention a decided improvement over the bobbin forms of armature then in use in regard to mechanical construction and compactness; but in its magnetic and electrical action it is radically imperfect, principally because it has only a single coil, which produces a very intermittent effect. The Alteneck armature, on the other hand, is wound with a number of coils or sections of wire in different planes, and is therefore continuous and steady in its action, like the Gramme armature. The only difference in principle between these two important types of armature is the fact that the iron core of the Gramme armature is in the form of a ring, while that of the Alteneck armature is a drum or cylinder. In fact, these terms are more commonly employed to designate the two types of armatures than the names of their inventors. Up to that time the history of electric lighting had been the history of the electric generator, because a good source of current had first to be obtained before any real progress could be made in applying electricity to the purpose of lighting. But the dynamo machine having been brought up to a reasonably practical form, it was available to form a solid basis for the astonishingly rapid development of practical electric lighting which then began. At the same time that the dynamo was being improved the problem of producing a satisfactory electric lamp was also being grappled with; but no very successful results had been obtained. Serrin in 1857, and others, had constructed arc lamps, or what were then called "regulators," which consisted of the electric arc between carbon points such as was produced long before by Davy, with the addition of a clock-work or other mechanism for feeding the carbons together as they burned away.

The incandescent lamp progressed at first even more slowly and imperfectly than the arc lamp. Crude forms of lamps were devised and made by Starr and King in 1845, Staite in 1848, and others; but none of these attempts can be looked upon as anything more than interesting experiments which laid the foundation for further progress. In 1876 there existed fairly satisfactory forms of dynamo machines and of arc lamps, and there

were crude forms of incandescent lamps; but up to that time the work that had been done consisted of separate and incomplete experiments. What was lacking was a *complete* set or system of apparatus which could be used to produce electric lighting in a practical way, or rather *commercial* way. This putting together of the necessary elements, even though they may already exist separately, is often a more important and difficult step in the creation of a new art than the invention of the individual parts, however essential each may be. In 1878 and 1879, the times being in that peculiar state when they are ripe for very rapid advance, which condition usually precedes all great inventions or industrial enterprises, there occurred almost simultaneously the bringing forth of several more or less complete systems of electric lighting. At that time the most serious difficulty was the so-called "subdivision" of the electric light; that is, the running of several lamps from the same source of current, or on the same circuit, without interfering with each other. This bugbear was greatly exaggerated, and was much discussed by scientific and technical men at that time, some of whom maintained that the subdivision was not only practically but theoretically impossible. The overcoming of this difficulty was therefore the primary object of the electric-lighting systems first introduced. Three radically different methods were almost simultaneously brought out, and put into quite extensive practical use. These three systems were invented and developed by Jablochkoff of Paris; Brush of Cleveland, O.; and Edison of Menlo Park, N.J. In the Jablochkoff system the subdivision of the electric light was accomplished by using a form of lamp called an electric candle, which was first invented by him in 1876. It consists of two thin pencils of carbon held at a fixed distance apart by insulating material in the form of a strip of kaolin. All that was necessary to operate a number of these lights on the same circuit successfully was to connect them by wires in a simple series, so that the current flowed through them one after another. The arc formed at each lamp was necessarily of constant length, and there was no tendency for one lamp to act differently from the others, or interfere with them in any way. An alternating current dynamo was employed to supply the current, in order that the two pencils should burn at the same rate. The Jablochkoff system has the

practical difficulties of requiring a new candle to be switched on every two hours, and the cost of the candles made the light rather expensive. It was sufficiently developed to be used for lighting the Avenue de L'Opéra and other places in Paris in 1878, and it was also introduced and used in a few places in America; but the objections stated above prevented it from being a permanent success commercially.

In the Brush system, brought out in 1878, arc lamps with regulating mechanism practically identical with those employed to-day were operated in series on a single circuit. The success of this system was due to the fact that it included a complete set of apparatus; that is, a dynamo having a current regulator, and arc lamps with differential coil regulators and simple ring-clutch mechanism, which lamps could be operated satisfactorily in series. Brush also invented the "double-carbon" lamp; that is, a lamp in which a second pair of carbons are automatically thrown into action when the first pair are used up. Before the introduction of inclosed arc lamps in 1893 this feature was practically essential for all-night arc lighting, as in the case of most street-lamps. In short, Brush gave to the public a system in which the various elements were reasonably good in themselves, and co-operated to produce a fairly economical and generally satisfactory method of lighting. Good business management also contributed largely to the wide use and original success of the Brush apparatus.

The Edison system, which was developed experimentally during 1878–1879, and brought out commercially in 1880, made use of the incandescent instead of the arc lamp. The Edison system contained the necessary elements for a successful use of the incandescent lamp, which elements had not been known or used previously, although the system is apparently very simple. These essential elements are: First, a dynamo having an armature with a very low internal resistance; and the armature introduced by Edison did not have more than one-fifth to one-tenth of the resistance of similar machines used by others prior to that time. Second, a constant potential or electrical pressure was maintained throughout the system of conductors, to which the lamps were connected in parallel, that is, in branch circuits, so that the turning on or off or breaking of a lamp did not affect the others. Third, the lamps consisted of high-resistance carbon filaments

hermetically sealed in glass globes in an almost perfect vacuum. High-resistance filaments are practically necessary to enable the use of reasonably high voltage, which greatly reduces the weight of copper required for the conductors, and a vacuum is required to prevent the destruction of the filament and the loss of heat by convection. At the same time that the Edison system was brought out, or soon after, other inventors were working on systems similar to the above. Important contributions to the progress of incandescent lighting were made in lamps and other devices by Sawyer and Man, Maxim and Weston, in America; also by Swan and Lane Fox in England. In the field of arc lighting, Thomson and Houston brought out a complete and very successful system, which had the radical advantage over the Brush system that the regulator for controlling the current and keeping it constant was superior to that employed by Brush. Indeed, the great success of the Thomson-Houston system was largely due to the very ingenious and effective regulator which they applied to their dynamo. Another arc-lighting system was brought out by Weston; but this also was defective in not having a satisfactory current regulator, although the dynamo and lamp were exceedingly well designed and constructed, considering the time at which they were made. In Europe, arc-lighting systems have been developed by Siemens, Krizig & Piette (the "Pilsen lamp"), Crompton, Gulcher, and other inventors and manufacturers; but arc lighting in Europe is not as popular or as extensively used as in this country.

A system of electric lighting by means of alternating current transformers was invented by Gaulard and Gibbs in 1882. This system was based on the early experimental work with induction coils by Faraday in 1831, Henry in 1832, Page in 1835, Sturgeon in 1837, Ruhmkorff in 1851, and others. Gaulard and Gibbs made the fatal error of running the transformers in series, which is impracticable. In 1885 Zipernowsky, Deri, and Blathy brought out a system in which this mistake was corrected, the transformers being worked in parallel. The alternating current transformer system was extensively and successfully introduced in the United States in 1887 by the efforts of Westinghouse, Stanley, and others. The great saving in the amount of copper required for the distributing conductors in this system caused it to be

rapidly and widely adopted. In the meantime, the dynamo machine was being gradually but steadily perfected by the various inventors and manufacturers, for use in their electric-lighting systems. Edison, Brush, Thomson, Houston, and Weston, all contributed to this progress. The multipolar dynamo was developed by Elphinstone and Vincent in 1879 and 1880, and by Schuckert, Gramme, Gulcher, Mordey, and others. The theoretical study of the dynamo was taken up by Clausius, Sir William Thomson, and Frölich. The last-named brought out in 1880 a working theory which is still of practical value. A great advance in the theory and practical design of dynamos was made by J. and E. Hopkinson in 1886.* Their paper laid down the correct theory, and embodied a method of designing the magnetic circuit of dynamo machines, which up to that time had been very imperfectly understood; and most machines at that time were very bad in this respect. Kapp brought out in 1887 a similar method of designing the field magnets of dynamos; but it was largely empirical, and not so complete and scientific as the Hopkinson method, which is now generally used by the best electrical engineers. Hopkinson and Edison † independently invented the three-wire system of distribution, which makes a considerable saving in the amount of copper required for low-tension circuits. Incandescent lamps have gradually been improved in cheapness and efficiency, and the mechanism of arc lamps has been perfected from time to time. Great improvements have been made in the last few years in the construction of large direct-coupled steam-engines and multipolar dynamos for central stations. Enormous progress has also been made in the general perfection of the various details of electric-lighting plants. The insulation of electrical conductors has been very greatly improved. Storage batteries have been extensively applied to electric-light stations and isolated plants to secure greater flexibility, economy, and reliability. The introduction of the inclosed arc lamp by L. B. Marks in 1893 has extended the life of a pair of carbons from 8 to 100 hours, thereby greatly reducing the cost and trouble of renewing them. Alternating-current arc lamps, both open and inclosed, have been developed to the point of rivalry with the direct-current

* *Philosoph. Transact. of the Royal Society.*

† U. S. Patent No. 274290, March, 20, 1883.

types. The Nernst lamp,* brought out in 1899, has a filament composed of certain metallic oxides which must first be heated by a flame or auxiliary electrical device in order to become a conductor. This type has a higher efficiency than the ordinary carbon filament-lamps. The Hewitt lamp† first exhibited in 1901 has a still higher efficiency. It consists of a tube containing mercury vapor. The various electric lamps are considered in Volume II.

For further study of the general history of lighting, the reader is referred to the following:—

Histoire du Luminaire depuis l'époque romaine jusqu'au XIX^e. Siècle, par Henri-René D'Allemagne, Paris, 1891.

This is a voluminous treatise on the history of all methods of artificial illumination from ancient to modern times. The artistic side is most prominent, but technical matters of construction and operation are also considered.

For the history of electric lighting reference may be made to *The Electric Light*, by Alglave and Boulard; translated by T. O'Conor Sloane; edited by C. M. Lungren.

Electric Illumination, by James W. Dredge, two vols., London, 1883–1885, contains the most complete account of the history of electric lighting prior to the dates of publication, each form of dynamo and lamp being described in detail.

Arc and Glow Lamps, by Julius Maier, London, 1886, contains illustrations and descriptions of many forms of lamps. *The Evolution of the Electric Incandescent Lamp*, by F. L. Pope, Elizabeth, N. J., 1889, gives a detailed account of the early work of Sawyer and Man, and Edison. Marsden J. Perry made an address on the history of electric lighting before the National Electric Association, February, 1891 (*Elec. World*, Feb. 28, 1891); and Charles F. Brush gave very interesting personal reminiscences of the early history of arc lighting before the same body in February, 1895 (*Elec. World*, March 2, 1895).

A very complete history of the dynamo is contained in Thompson's *Dynamo-Electric Machinery* (Fifth Edition, pages 5–21).

* U. S. Patents Nos. 685, 724–32, Oct. 29, 1901. *Transactions Amer. Inst. Elec. Eng.*, Aug. 1901.

† *Electrical Review*, New York, April 27, 1901.

CHAPTER III.

GENERAL UNITS AND MEASURES.

THE general principles of electricity should first be studied and understood before one attempts to take up the subject of electric lighting or other branch of electrical science, whether theoretical or applied. In electrical books it has been a common practice to devote a great deal of space to first principles; in fact, it is no exaggeration to say that from one-quarter to one-half of almost every book which treats of some particular branch of applied electricity is taken up by a discussion of the elementary facts of electricity and magnetism. The result has been that the first parts of almost all electrical books are practically identical, and the subject itself is hardly touched until nearly one-half of the space has been used up, which greatly curtails the real subject-matter. This practice is obviously unnecessary, and most readers skip the first part before they find anything that interests them. The source from which to obtain a sufficient knowledge of the fundamental principles is some elementary or general treatise; and the reader, if not already familiar with the subject, is referred to such treatises, and recommended to acquire a general knowledge of electricity before attempting to master electric lighting or any other application of electricity. There are, however, certain important facts and principles which are of special significance in connection with any particular subject.

Furthermore, there is a certain amount of choice in the selections of units, standards, terms, and definitions, which make it desirable for each author to specify exactly which of these he employs; otherwise, considerable confusion and uncertainty might arise in the mind of the reader, because different authors employ quite different standards, terms, etc. There is, fortunately, a strong tendency towards uniformity and definiteness in regard to electrical units and terms, and each year sees considerable advance in this direction. The most important example of this is the universal adoption of the "International" volt, ohm, and other electrical

units, which are no longer abstract, as they formerly were, but are concrete and material standards. We have, on the other hand, quite a large increase in the number of electrical terms and units, due to the rapid progress of knowledge; but such new terms must necessarily be experimental and unsettled until they are found to be not only correct, but useful. In fact, the test of utility alone largely determines the question of whether a new term or unit is worthy of adoption. The outcry against the introduction of any new electrical term is futile, because they are the inevitable result of progress and more exact knowledge. The simple fact is, that the time is soon coming when no one person can be master of more than one or at most a few branches of electricity. On the other hand, the multiplication of new units and terms can be, and often is, carried too far. It is not desirable to have a name for every possible quantity or combination of quantities, and it is still more superfluous to give names to the *reciprocals* of all these quantities. Such matters, however, take care of themselves, and time will show what is necessary or desirable. It may be the duty of future electrical congresses to abolish units and terms which are found to be useless.

In the present work it was thought best to put the various principles with the particular subject to which they naturally belong; for example, the data of electromagnetism are given in connection with the dynamo. There are, however, certain fundamental units which are used in many branches, and a few of these are given in this chapter for convenience. The necessity for this is increased by the unfortunate fact that both the metric and English systems of measure are used in electrical engineering; and we are practically forced to use both, and often the two systems are actually mixed in the same sentence! Hence the ratios for converting one system into the other are often needed.

There seems to be no way to avoid this at present, and the transition must be made gradually. Indeed, it will be extremely difficult to change the measurements of wires, machines, etc., which are always manufactured and measured in terms of inches and feet. But in some cases the use of centimeters and other metric units involves no serious trouble, and the centigrade thermometer scale can often be substituted for the senseless Fahrenheit scale, thus accustoming ourselves to the change.

In steam-engineering, however, the English system is still employed almost exclusively, and in many cases we must even use Fahrenheit heat units in order to be understood. It does more harm than good to attempt to force these matters; and a book in the English language which uses one system exclusively is very inconvenient to a large fraction of its readers, and is not suited to the present times.

The following tables are given to facilitate the conversion of metric into English units, or *vice versa*. The logarithms (six-figure) of each number are also given. In most cases four-place logarithms are sufficiently accurate; hence a space is left between the fourth figure and the last two, so that the latter may be easily omitted. Approximate values for mental calculations are given in many instances, the error being usually less than one per cent.

MEASURES OF LENGTH.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Millimeters in one inch	25	25.4	1.4048 34
Centimeters in one inch	2½	2.54	.4048 34
Centimeters in one foot	30½	30.48	1.4840 15
Meters in one foot	$\frac{4}{13}$	.30480	$\bar{1}$.4840 15
Meters in one yard	$\frac{11}{12}$	.91440	$\bar{1}$.9611 36
Meters in one statute mile		1609.35	3.2066 50
Kilometers in one mile	1⅗	1.60935	.2066 50
Inches in one centimeter	⅖	.3937	$\bar{1}$.5951 65
Inches in one meter	39⅓	39.37	1.5951 65
Feet in one meter	3¼	3.28083	.5159 87
Feet in one mile		5280.	3.7226 34
Feet in one kilometer		3280.83	3.5159 87
Yards in one meter	1$\frac{1}{11}$	1.09361	.0388 65
Yards in one mile		1760.	3.2455 13
Miles in one kilometer	⅝	.62137	$\bar{1}$.7933 50

MEASURES OF AREA.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Square millimeters in one square inch		645.16	2.8096 68
Square centimeters in one square inch	6½	6.4516	.8096 68
Square centimeters in one square foot		929.03	2.9680 30
Square meters in one square foot	$\frac{1}{11}$	.092903	.9680 30
Square kilometers in one square mile	2⅗	2.59	.4133
Square inches in one square centimeter	$\frac{2}{13}$	.155	$\bar{1}$.1903 32
Square inches in one square meter		1550.	3.1903 32
Square feet in one square meter	10¾	10.764	1.0319 74
Square yards in one square meter	1⅕	1.196	.0777 31
Square miles in one square kilometer	⅜	.3861	$\bar{1}$.5867

MEASURES OF VOLUME.

	APPROX. VALUE.	ACTUAL. NUMBER.	LOGARITHM.
Cubic centimeters in one cubic inch	$16\frac{2}{5}$	16.387	1.2145
Cubic centimeters in one cubic foot		28316.	4.4520 30
Cubic meters in one cubic yard	$\frac{3}{4}$	.7645	$\bar{1}$.8833 77
Cubic inches in one cubic centimeter	$\frac{1}{16}$	.06102	$\bar{2}$.7854 72
Cubic feet in one cubic meter	$35\frac{1}{3}$	35.32	1.5480 21
Cubic yards in one cubic meter		1.308	.1166
Cubic centimeters in one quart (U. S. Liquid) . .		946.3	2.9760 30
Cubic centimeters in one gallon (Imperial) . . .		4542.	3.6572 50
Liters in one quart (U. S. Liquid)		.9463	$\bar{1}$.9760 30
Liters in one gallon (Imperial)	$4\frac{1}{2}$	4.542	.6572 50
Cubic inches in one liter		61.02	1.7854 72

MEASURES OF WEIGHT.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Grams in one pound (avoirdupois)		453.59	2.6566 66
Kilograms in one pound (avoirdupois)	$\frac{10}{22}$	.45359	$\bar{1}$.6566 66
Milligrams in one grain	65	64.799	1.8115 68
Grains in one gram	$15\frac{1}{2}$	15.432	1.1884 30
Ounces (avdp.) in one kilogram	$35\frac{1}{4}$	35.274	1.5474 55
Pounds (avdp.) in one kilogram	$2\frac{2}{10}$	2.2046	.3433 34
Short tons (2000 lbs.) in one metric ton (1000 kg.)	$1\frac{1}{10}$	1.1023	.0423 04
Long tons (2240 lbs.) in one metric ton (1000 kg.)	1	.9842	$\bar{1}$.9930 83
Metric tons (1000 kg.) in one short ton (2000 lbs.)	$\frac{9}{10}$	.90719	$\bar{1}$.9576 96

COMPOUND UNITS. (WORK AND PRESSURE.)

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Kilogram-meters in one foot-pound		.13825	$\bar{1}$.1406 65
Foot-pounds in one kilogram-meter	$7\frac{1}{4}$	7.233	.8593 20
Kilograms per sq. cm. (pressure) in one lb. per sq. in.		.07031	$\bar{2}$.8470 14
Pounds per sq. inch in one kg. per sq. cm. . . .	$14\frac{1}{4}$	14.223	1.1529 90

MEASURES OF HEAT.

These are given in connection with the subjects of the steam-engine and arc and incandescent lamps, where they naturally belong. The conversion of centigrade temperatures into Fahrenheit, or *vice versa*, has to be performed so often, however, that the data are given here. To convert centigrade degrees into Fahrenheit, multiply by $\frac{9}{5}$ or 1.8, and add 32. To convert Fahrenheit degrees into centigrade, subtract 32, and multiply by $\frac{5}{9}$; that is, —

$$t_f = \tfrac{9}{5}\, t_c + 32 \qquad \text{and} \qquad t_c = \tfrac{5}{9}\,(t_f - 32).$$

The values of the various units of heat are not always given exactly the same, for the reason that the original value obtained by Joule for the mechanical equivalent of heat was 772 foot-pounds for one pound of water heated one degree Fahrenheit. The later experiments of Rowland show that this should be about 780 foot-pounds,* depending upon the specific heat of water and the force of gravity.

* Everett's C. G. S. *System of Units*, 1891 Edit., pp. 99–101.

Accepting the latter value, we have the following relations: —

780 ft.-lbs. per lb.-deg. F.
1404 ft.-lbs. per lb.-deg. C.
428 kgm.-meters per kg.-deg. C.
4.2×10^7 ergs per grm.-deg. C.
4.2 Joules (Watt-seconds) per grm.-deg. C.

The grm.-deg. C. is the amount of heat required to raise the temperature of one gram of water one degree Cent., and is called the gram-calorie.

ELECTRICAL UNITS.

Formerly the electrical units were defined somewhat abstractly, and there were considerable discrepancies between the various determinations of the ohm. The result was that three values for the ohm and volt have been adopted and used. These are the British Association (B.A.) ohm and volt, the "Legal" ohm and volt, and, finally, the *International* ohm and volt. The value of the ampere has not changed materially since its absolute value was easily and accurately obtained by the tangent galvanometer.

This confusion has been overcome by the recommendations of the International Electrical Congress, held at Chicago, August, 1893, which have been adopted and legalized by the United States, England, Germany, and other countries.

Thus the ohm, volt, and other electrical units have definite, and probably *final*, values all over the world.

The Act of the United States Congress legalizing these units is as follows:—

AN ACT

To define and establish the units of electrical measure.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That from and after the passage of this Act the legal units of electrical measure in the United States shall be as follows: —

First. The unit of resistance shall be what is known as the International ohm, which is substantially equal to one thousand million units of resistance of the centimeter-gram-second system of electro-magnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice fourteen and four thousand five hundred and twenty-one ten-thousandths (14.4521) grams in mass, of a constant cross-sectional area, and of the length of one hundred and six and three tenths (106.3) centimeters.

Second. The unit of current shall be what is known as the international ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electro-magnetic units, and is the practical equivalent of the unvarying current, which, when passed through a solution of nitrate of silver in water

in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths (.001118) of a gram per second.

Third. The unit of electro-motive force shall be what is known as the international volt, which is the electro-motive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of an international ampere, and is practically equivalent to one thousand fourteen hundred and thirty-fourths ($\frac{1000}{1434}$) of the electro-motive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of fifteen degrees centigrade, and prepared in the manner described in the standard specifications.

Fourth. The unit of quantity shall be what is known as the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

Fifth. The unit of capacity shall be what is known as the international farad, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

Sixth. The unit of work shall be the Joule, which is equal to ten million units of work in the centimeter-gram-second system, and which is practically equivalent to the energy expended in one second by an international ampere in an international ohm.

Seventh. The unit of power shall be the Watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is practically equivalent to the work done at the rate of one Joule per second.

Eighth. The unit of induction shall be the Henry, which is the induction in a circuit when the electro-motive force induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second.

SEC. 2. That it shall be the duty of the National Academy of Sciences to prescribe and publish, as soon as possible after the passage of this Act, such specifications of details as shall be necessary for the practical application of the definitions of the ampere and volt hereinbefore given, and such specifications shall be the standard specifications herein mentioned.

Approved July 12, 1894.

The specifications prescribed by the National Academy of Sciences in accordance with the last section of the above act are as follows:—

SPECIFICATIONS FOR THE PRACTICAL APPLICATION OF THE DEFINITIONS OF THE AMPERE AND VOLT.

Specification A.— *The Ampere.*

IN employing the silver voltameter to measure currents of about one ampere, the following arrangements shall be adopted:—

The cathode on which the silver is to be deposited shall take the form of a platinum bowl not less than 10 centimeters in diameter, and from 4 to 5 centimeters in depth.

The anode shall be a disk or plate of pure silver some 30 square centimeters in area, and 2 or 3 millimeters in thickness.

This shall be supported horizontally in the liquid near the top of the solution by a silver rod riveted through its center. To prevent the disintegrated silver which is formed on the anode from falling upon the cathode, the anode shall be wrapped around with pure filter paper, secured at the back by suitable folding.

The liquid shall consist of a neutral solution of pure silver nitrate, containing about 15 parts by weight of the nitrate to 85 parts of water.

The resistance of the voltameter changes somewhat as the current passes. To prevent these changes having too great an effect on the current, some resistance besides that of the voltameter should be inserted in the circuit. The total metallic resistance of the circuit should not be less than 10 ohms.

Method of making a Measurement. — The platinum bowl is to be washed consecutively with nitric acid, distilled water, and absolute alcohol; it is then to be dried at 160° C., and left to cool in a desiccator. When thoroughly cool it is to be weighed carefully.

It is to be nearly filled with the solution, and connected to the rest of the circuit by being placed on a clean insulated copper support to which a binding-screw is attached.

The anode is then to be immersed in the solution so as to be well covered by it, and supported in that position; the connections to the rest of the circuit are then to be made.

Contact is to be made at the key, noting the time. The current is to be allowed to pass for not less than half an hour, and the time of breaking contact observed.

The solution is now to be removed from the bowl, and the deposit washed with distilled water, and left to soak for at least six hours. It is then to be rinsed successively with distilled water and absolute alcohol, and dried in a hot-air bath at a temperature of about 160° C. After cooling in a desiccator it is to be weighed again. The gain in mass gives the silver deposited.

To find the time-average of the current in amperes, this mass, expressed in grams, must be divided by the number of seconds during which the current has passed and by 0.001118.

In determining the constant of an instrument by this method, the current should be kept as nearly uniform as possible, and the readings of the instrument observed at frequent intervals of time. These observations give a curve from which the reading corresponding to the mean current (time-average of the current) can be found. The current, as calculated from the voltameter results, corresponds to this reading.

The current used in this experiment must be obtained from a battery, and not from a dynamo, especially when the instrument to be calibrated is an electro-dynamometer.

Specification B. — *The Volt.*

Definition and Properties of the Cell. — The cell has for its positive electrode, mercury, and for its negative electrode, amalgamated zinc; the electrolyte consists of a saturated solution of zinc sulphate and mercurous sulphate. The electro-motive force is 1.434 volts at 15° C.; and between 10° C. and 25° C., by

the increase of 1° C. in temperature, the electro-motive force decreases by 0.00115 of a volt.

1. *Preparation of the Mercury.* — To secure purity it should be first treated with acid in the usual manner, and subsequently distilled *in vacuo.*

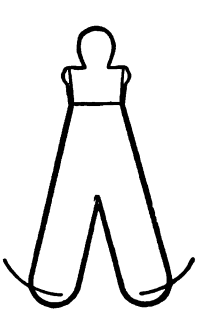
2. *Preparation of the Zinc Amalgam.* — The zinc designated in commerce as "commercially pure" can be used without further preparation. For the preparation of the amalgam one part by weight of zinc is to be added to nine (9) parts by weight of mercury, and both are to be heated in a porcelain dish at 100° C., with moderate stirring until the zinc has been fully dissolved in the mercury.

3. *Preparation of the Mercurous Sulphate.* — Take mercurous sulphate, purchased as pure, mix with it a small quantity of pure mercury, and wash the whole thoroughly with cold distilled water by agitation in a bottle; drain off the water, and repeat the process at least twice. After the last washing, drain off as much of the water as possible. (For further details of purification, see Note A.)

4. *Preparation of the Zinc Sulphate Solution.* — Prepare a neutral saturated solution of pure re-crystallized zinc sulphate, free from iron, by mixing distilled water with nearly twice its weight of crystals of pure zinc sulphate, and adding zinc oxide in the proportion of about 2 per cent by weight of the zinc sulphate crystals, to neutralize any free acid. The crystals should be dissolved with the aid of gentle heat, but the temperature to which the solution is raised must not exceed 30° C. Mercurous sulphate, treated as described in 3, shall be added in the proportion of about 12 per cent by weight of the zinc sulphate crystals, to neutralize the free zinc oxide remaining, and then the solution filtered, while still warm, into a stock bottle. Crystals should form as it cools.

5. *Preparation of the Mercurous Sulphate and Zinc Sulphate Paste.* — For making the paste, two or three parts by weight of mercurous sulphate are to be added to one by weight of mercury. If the sulphate be dry, it is to be mixed with a paste consisting of zinc sulphate crystals and a concentrated zinc sulphate solution, so that the whole constitutes a stiff mass, which is permeated throughout by zinc sulphate crystals and globules of mercury. If the sulphate, however, be moist, only zinc sulphate crystals are to be added; care must, however, be taken that these occur in excess, and are not dissolved after continued standing. The mercury must in this case also permeate the paste in little globules. It is advantageous to crush the zinc sulphate crystals before using, since the paste can then be better manipulated.

To set up the Cell. — The containing glass vessel, represented in the accompanying figure, shall consist of two limbs closed at bottom and joined above to a common neck fitted with a ground-glass stopper. The diameter of the limbs should be at least 2 centimeters, and their length at least 3 centimeters. The neck should be not less than 1.5 centimeter in diameter. At the bottom of each limb a platinum wire of about 0.4 millimeter diameter is sealed through the glass.



To set up the cell, place in one limb pure mercury, and in the other hot liquid amalgam, containing 90 parts

mercury and 10 parts zinc. The platinum wires at the bottom must be completely covered by the mercury and the amalgam respectively. On the mercury place a layer one centimeter thick of the zinc and mercurous sulphate paste described in 5. Both this paste and the zinc amalgam must then be covered with a layer of the neutral zinc sulphate crystals one centimeter thick. The whole vessel must then be filled with the saturated zinc sulphate solution, and the stopper inserted so that it shall just touch it, leaving, however, a small bubble to guard against breakage when the temperature rises.

Before finally inserting the glass stopper, it is to be brushed round its upper edge with a strong alcoholic solution of shellac, and pressed firmly in place. (For details of filling the cell, see Note B.)

NOTES TO THE SPECIFICATIONS.

(A) *The Mercurous Sulphate.* — The treatment of the mercurous sulphate has for its object the removal of any mercuric sulphate, which is often present as an impurity.

Mercuric sulphate decomposes in the presence of water into an acid and a basic sulphate. The latter is a yellow substance — turpeth mineral — practically insoluble in water; its presence, at any rate in moderate quantities, has no effect on the cell. If, however, it be formed, the acid sulphate is also formed. This is soluble in water, and the acid produced affects the electromotive force. The object of the washings is to dissolve and remove this acid sulphate, and for this purpose the three washings described in the specification will suffice in nearly all cases. If, however, much of the turpeth mineral be formed, it shows that there is a great deal of the acid sulphate present; and it will then be wiser to obtain a fresh sample of mercurous sulphate, rather than to try by repeated washings to get rid of all the acid.

The free mercury helps in the process of removing the acid; for the acid mercuric sulphate attacks it, forming mercurous sulphate.

Pure mercurous sulphate, when quite free from acid, shows on repeated washing a faint yellow tinge, which is due to the formation of a basic mercurous salt distinct from the turpeth mineral, or basic mercuric sulphate. The appearance of this primrose-yellow tint may be taken as an indication that all the acid has been removed; the washing may with advantage be continued until this tint appears.

(B) *Filling the Cell.* — After thoroughly cleaning and drying the glass vessel, place it in a hot-water bath. Then pass through the neck of the vessel a thin glass tube, reaching to the bottom, to serve for the introduction of the amalgam. This tube should be as large as the glass vessel will admit. It serves to protect the upper part of the cell from being soiled with the amalgam. To fill in the amalgam, a clean dropping-tube about 10 centimeters long, drawn out to a fine point, should be used. Its lower end is brought under the surface of the amalgam, heated in a porcelain dish, and some of the amalgam is drawn into the tube by means of the rubber bulb. The point is then quickly cleaned of dross with filter paper, and is passed through the wider tube to the bottom, and emptied by pressing the bulb. The point of the tube must be so fine that the amalgam will come out only on squeezing the bulb. This process is repeated

until the limb contains the desired quantity of the amalgam. The vessel is then removed from the water-bath. After cooling, the amalgam must adhere to the glass, and must show a clean surface with a metallic luster.

For insertion of the mercury, a dropping-tube with a long stem will be found convenient. The paste may be poured in through a wide tube reaching nearly down to the mercury, and having a funnel-shaped top. If the paste does not move down freely, it may be pushed down with a small glass rod. The paste and the amalgam are then both covered with the zinc sulphate crystals before the concentrated zinc sulphate solution is poured in. This should be added through a small funnel, so as to leave the neck of the vessel clean and dry.

For convenience and security in handling, the cell may be mounted in a suitable case, so as to be at all times open to inspection.

In using the cell, sudden variations of temperature should, as far as possible, be avoided, since the changes in electro-motive force lag behind those of temperature.

Respectfully submitted.

HENRY A. ROWLAND,
Chairman.
HENRY L. ABBOT,
GEORGE F. BARKER,
CHARLES S. HASTINGS,
ALBERT A. MICHELSON,
JOHN TROWBRIDGE,
CARL BARUS,
Committee.

At a meeting of the National Academy of Sciences, held in New York Feb. 9, 1895, the above report was accepted and unanimously adopted by the Academy.

At the same meeting it was voted by the National Academy of Sciences to prescribe and to publish the specifications of details necessary for the practical application of the definitions of the ampere and volt, as required by the law of July 12, 1894.

O. C. MARSH,
President of the National Academy of Sciences.
ASAPH HALL,
Home Secretary.

MAGNETIC UNITS.

These are given in the beginning of the chapter on "Principles and Construction of the Dynamo," where they may be more conveniently and concretely considered.

Miscellaneous Units, Standards, and Terms employed in the various branches of the subject are defined or explained as far as possible where they occur.

CHAPTER IV.

CLASSIFICATION AND SELECTION OF ELECTRIC-LIGHTING SYSTEMS.

ELECTRIC-LIGHTING classification, like that of almost any subject, is more or less arbitrary, and is adopted merely for convenience. Considered in this light, classification is a great help; but we should carefully avoid the common mistake of forcing it too far by attempting to make the facts fit the classification, instead of the classification fitting the facts.

Electric-lighting apparatus may be classified with reference to various considerations. For example, it may be classified with reference to the system as a whole, or with reference to some of its most important elements or characteristics.

Central Stations and Isolated Plants. — Considered as a whole, electric-lighting systems may be divided into two important classes, — central stations and isolated plants. These two classes sometimes merge into each other, and peculiar cases might occur which would be on the dividing line; but ordinarily the distinction between the two is radical, and introduces considerable differences in design, construction, and operation. In fact, these two types of plant must be considered as quite different problems in electrical engineering, and usually there is no difficulty in distinguishing between them. A central station electric-lighting system is usually extensive and elaborate technically, and quite complicated and difficult in its business management. It consists of a large and complete collection of machinery for generating and controlling the electric current. This generating-plant is usually contained in one or more buildings entirely devoted to it, and probably specially built for it. The central station is usually owned and operated by a company having no other business. From the central station a large number of electrical conductors run out in every direction. These conductors supply electric current to feed lamps for many different purposes, and for the use of many different and independent customers; and a separate

measurement or estimate of current and charge therefor is made in the case of each customer.

Isolated electric-lighting plants, on the other hand, are comparatively small and simple in construction and management. They are usually entirely local; that is, the plant supplies current for lighting a single building or group of buildings. The generating plant or machinery is ordinarily located in the cellar, or some small portion of the building. An isolated plant usually supplies current only to its owner or his tenants, and is owned and operated by a private individual, company, or institution, and constitutes only a small and incidental part of its affairs. Light is supplied to the various buildings, or parts of the building, usually without attempting to make separate measurements or charges, which eliminates the somewhat troublesome element of meters, and greatly simplifies the business management.

Incandescent and Arc Lighting. — Electric lighting may also be classified with reference to the *lamps;* that is, we have incandescent-lighting and arc-lighting systems. A few years ago it could have been said that incandescent systems were operated at constant potential, that is, constant voltage, the lamps being connected to the circuit in parallel; and it could have been said that arc systems were almost invariably supplied with a constant current, that is, one having a fixed number of amperes, the lamps being arranged in series. This distinction still holds good to a certain extent; but about the year 1890 there began a general introduction of arc lamps on incandescent circuits with constant-potential current. These lamps possess the advantage over the ordinary constant-current lamps that the current is of low potential; that is, only about one or two hundred volts instead of two to five thousand volts, which are usually employed on constant-current arc circuits. On the other hand incandescent lamps are sometimes operated on the constant-current circuit, being called series-incandescent lamps; but these are much less common than the constant-potential type. They are used chiefly for street lighting on what is called the "municipal system." (Vol. II, p. 25.)

The advantages of incandescent electric lighting are:—

The fact that lamps of any desired size from one candle-power to fifty or one hundred can be had and easily substituted one for the other. The light is steady and agreeable in quality, being in

those respects better than a very good gas light. It is practically free from danger of setting fire even to the most inflammable material. The lamps can be put in almost any place or position. The wires required to feed an incandescent lamp are small, and can be easily placed in fixtures, mouldings, etc., and thus concealed.

The arc light, on the other hand, has the advantage of being simpler and cheaper to install, particularly in regard to wiring; and it gives more light for a given amount of electrical energy than an incandescent lamp. The ordinary arc lamp, including open, inclosed, direct and alternating current types, consumes about 450 or 500 watts and gives about 200 to 400 candle-power. This is at the rate of about 1.5 to 2.5 watts per candle-power. The ordinary incandescent lamp requires 110 volts and .45 ampere, or about 50 watts, and gives 16 candle-power. This is at the rate of about 3.1 watts per candle-power. Therefore the arc lamp gives about 1.25 to 2 times as much light for the same amount of electric power. To offset this advantage, however, the arc lamp is quite limited in the range of its candle-power; that is to say, to obtain good results, an open arc requires a minimum of about 40 volts and 8 amperes in order to work well. If it is attempted to make an arc lamp very much smaller than this in power, it is apt to be unsteady and liable to go out entirely; and the same limitation applies generally to all arc lamps. It is possible to make arc lamps of greater candle-power than the ordinary, to almost any extent, even as high as several hundred thousand candle-power; but such lamps are only used for special purposes, such as search lights. Hence the arc lamp is not suited to places where small amounts of light are required, or where a uniform distribution of light is wanted.

In some cases arc lamps have been arranged to throw all their light upward against a whitened ceiling. In this way the direct light of the arc is not visible, and the indirect illumination obtained is much softer and more distributed. This arrangement, called the "inverted arc," has been quite successful in several places, and makes the arc lamp applicable where the incandescent lamp is ordinarily used, but is not very efficient.

The arc light is often objectionable because its great intensity and the glaring quality of its light are disagreeable, or even

actually injurious, to the eye, unless it is shaded by porcelain or ground glass, which absorbs about half the light, and sacrifices a large part of the power and economy. The color of the light, however, is almost pure white, and closely resembles sunlight in its quality, and is, therefore, sometimes desirable in shops, factories, etc., where colors are to be brought out in their true relations, or photographic operations are carried on. In a general way it can be said that incandescent lamps are suited to interior lighting and to comparatively small spaces, whereas arc lamps are adapted to outdoor lighting or to large spaces, such as railway stations, etc.

The arc light is often used for temporary illumination where work is being done in excavations, buildings, etc., at night. Its advantages in these cases are its great power, and the simplicity of wiring needed. The engines and dynamos employed for arc lighting do not require to regulate so perfectly as for incandescent lighting; and this is also an advantage for temporary installations, since it avoids the necessity for very fine machinery, or careful setting and adjustment of the same.

Alternating and Direct Currents. — The third classification of electric-lighting systems is in respect to *current;* and we have direct-current and alternating-current systems, the direct current being one which flows in one direction only, and the alternating being a rapidly reversed current. The following table shows the various direct and alternating current systems that are employed.

DIRECT CURRENT.	Dynamos alone.
	Dynamos and auxiliary secondary battery.
	Dynamos and dynamotors.
	Primary batteries.
ALTERNATING CURRENT.	Alternators alone.
	Alternators and transformers.
	Alternators and "step-up" and "step-down" transformers.
	Alternators with "step-down" transformers and rotary converters.

The general advantages of the direct-current system are: —

The potential or voltage is low. This applies, however, to incandescent and constant potential arc lamps, and not to constant current arc lamps. The direct current also possesses the advantage that motors of any desired size can be connected to the circuit and operated very satisfactorily. Direct currents are

also suited to electroplating or other electrometallurgical or electrochemical purposes, and storage batteries can be used with them. Direct currents are also largely free from peculiar actions and losses due to self-induction and electrostatic capacity, which may occur in the case of alternating currents. The great advantage of the alternating current is due to the fact that it can be generated at a high potential, usually 1100 or 2200 volts, and transmitted a considerable distance over a comparatively small wire without serious loss. This economy in the size of wire required is due to the fact that, since the potential in volts is high, the current in amperes, and therefore the cross-section of the wire needed, are small. When a point where lights are to be run is reached, the voltage is brought down by means of transformers to, say, 104 or 208 volts, and wires may be run about a house, for example, and carry this low-tension current, which has thus been made harmless. This ability to transform the alternating current from one voltage to another, as desired, by means of simple induction coils having no moving parts, is the great advantage to which the alternating current almost entirely owes its importance. The alternating current also has the advantage of requiring no commutator on the dynamo which generates it, two simple collecting rings being sufficient; but a separate machine or winding is required to furnish a direct current to excite the field magnet, and this involves a commutator.

The alternating current can also be regulated by means of the counter electromotive force of a "choke coil," which shuts off the current without wasting so much energy as the simple resistance coils used to control direct currents. Storage batteries cannot, however, be used with the alternating current. The relative merits and economy of the direct and alternating current systems have given rise to more discussion than any other subject in electrical engineering; and the question is still an unsettled one, even the most competent authorities not being agreed upon the matter. This problem involves a great many fine points, and would depend upon the conditions in each particular case. It is discussed more fully later in its bearing upon the problem of selecting a system in a given case. In this connection it is one of the most important questions which an electrical engineer is called upon to decide.

High and Low Potential. — The fourth and last classification of electric-lighting systems is with reference to the use of "high-tension" and "low-tension" currents. The term tension, however, is old-fashioned, and was formerly employed to designate what we now call potential or voltage. It is impossible to exactly define what constitutes a high-tension system, since much depends upon the circumstances and the point of view. If we look upon the question in its relation to fire risk or insurance, we find that "any circuit, attached to any machine or combination of machines, which develops a difference of potential, between any two wires, of over 10 volts and less than 550 volts shall be considered as a low-potential circuit." This statement is quoted from the "National Electrical Code," which has been generally adopted by the fire insurance authorities throughout the United States and Canada, being given in full in Appendix I of Volume II.

Potentials of less than 10 volts are not used for electric light or power except with small portable lamps or motors, and in most cases the voltage is above 100. Circuits that operate at 10 volts or less are confined almost entirely to telegraphy, telephony, or signalling, and are not considered dangerous, but the Code contains special rules applicable to them, the principal object being to protect such circuits from the high voltages carried by other wires. This class of circuits, especially in telegraphy, often employs voltages considerably higher, but the current is very small and is not of itself likely to cause any damage.

A high-potential system is one in which the voltage between any two wires is "over 550 volts and less than 3500 volts," according to the National Electrical Code. These figures are sometimes modified locally. The rules of the Department of Water Supply, Gas, and Electricity in New York City, for example, give 300 and 3000 volts as the limits of a high-potential system. This question is important because insurance and municipal rules must be obeyed, and the wiring and other construction required is quite different for high- and low-potential systems.

An extra-high-potential system is defined by the National Electrical Code to be one "which develops a difference of potential, between any two wires, of over 3500 volts." It is not allowable to bring it into buildings except power or sub-stations, unless the pressure is transformed down to 3500 volts or less.

While these rules apply principally to fire hazard, the comparative danger to life may be rated by the same limits of voltage.

The Selection of a System. — The classification given in the preceding pages may be tabulated in the following form, from which the choice of an electric-lighting system must be made: —

CLASSES.		SYSTEMS.
CENTRAL STATIONS.	1.	Incandescent. / Arc.
ISOLATED PLANTS.	2.	Direct. / Alternating.
	3.	High-tension. / Low-tension.

The actual selection of a certain system and type of apparatus for a particular case depends, of course, largely upon the peculiar circumstances that may exist, and the greatest care should be exercised in taking into consideration the local conditions which, rather than general principles, usually determine the success or failure of an electric-lighting plant. The safest guide is, of course, *experience*; and the engineer, if he does not himself possess the experience, should, if possible, find some case where the conditions resemble those with which he has to deal. By a careful study of the results obtained in the case selected as an example, one can often get the benefit of much experience which will save time and trouble, eliminate mistakes, and secure results that would not otherwise be possible.

It is foolish for an engineer to launch out without regard to the experience obtained by others at great cost in similar cases, on account of conceit or false pride, which makes him unwilling to profit by results already obtained. Many a partial or total failure would have been prevented by a little more carefulness and common-sense in this direction. It is almost always a mistake for an engineer to employ some untried method or apparatus solely upon his own knowledge and responsibility, unless it is absolutely necessary, or unless those who have to pay for the experiment understand the facts of the case; and when the engineer goes so far as to try his own inventions (in regard to which he is, of course, prejudiced), at the expense of others, it is positively dishonest. A certain amount of experiment and novelty is a necessary element of each engineering problem, and this con-

tributes to general improvement and progress; but experiments should usually be tried as such, and all persons interested should realize that one is being tried: in fact, the proper place for engineering experiments is in the experimental department of some company or institution. Nothing is more important or interesting than experiment, and the world would stand still without it; but in practical and regular work it is usually found that the simplest, most standard, and well-tried devices give by far the most satisfactory results. Radical and sensational departures from established practice are usually the cause of regret to all concerned.

The Size of Plant. — This the engineer must definitely know before making any exact plans or calculations. It is usually ascertained in terms of the number and distances of lamps that will be required, by making a thorough canvass of the city or town, or that portion of it which it is intended to light. The probable number of lamps which the station will supply when it first starts up, and what the number is likely to become afterward, are matters upon which the entire design and construction of the station depend.

Let us consider the simplest case first, and assume that the plant to be installed is an isolated one for lighting one building or group of buildings. In this case there is little or no uncertainty; and the direct-current, constant-potential system at about 110 or 220 volts would naturally be selected. Since the distances and lengths of wire required would be small, there would be no reason for using a high-tension system. Formerly the latter had to be introduced if arc lamps were used, but since 1890 many successful forms have been developed for operation on the low-voltage, constant-potential circuit. The fact that motors work so well on the latter, and that the Nernst, Hewitt, and other newer types of lamp are also adapted to it, has greatly extended the scope of this system.

This possibility of running both arc and incandescent lamps on the same circuit avoids the necessity of putting in special constant-current machines to run the arc lamps, which was formerly done even in the case of isolated plants, and involved considerable extra first cost and much more trouble in running the plant. Arc lamps operated in this way on a low-tension cir-

cuit are limited in regard to distance from the generator, as in the case of low-tension incandescent lamps; but it has occurred to the author that since a certain amount of resistance is needed in series with constant-potential arc lamps, it is possible to use the wires leading to the lamp for that resistance, thereby avoiding a special resistance in the lamp, and permitting the lamp to be placed at a considerable distance from the generator.

The single-phase alternating current is rarely used without transformers for low-potential service. In almost all cases it has been generated at about 1,000 or 2,000 volts to be transmitted several miles and locally transformed to about 100 or 200 volts for electric lighting. Its advantage lies in the economy of copper secured by high pressure. This system is obviously unsuited to isolated plants where the distances are short, as in a single building or group of buildings. The conductors would cost practically the same as for a low-potential installation, and the transformers involve extra expense, trouble, and danger. It is possible to generate single-phase currents at 110 or 220 volts and supply lamps without transformers as in the ordinary direct-current system. This, however, has been unusual, chiefly because the single-phase current is not well adapted to the operation of motors, in most cases power as well as light being desired.

The two-phase and three-phase currents are generally employed for the long-distance transmission of power at high potential and with transformers. They are also used in many low-potential isolated plants where power is the chief consideration, the polyphase induction or even synchronous motors being successful machines. For isolated plants in which lighting is the principal service the direct current at 110 or 220 volts is almost universal. Motors can also be operated exceedingly well and storage batteries used in connection with it. For these reasons this system is also widely adopted for isolated power plants, especially for variable speed.

Central Stations.—When isolated plants become very large, as, for example, in the case of a number of factories or other buildings scattered along some distance apart, it then becomes practically the same question as selecting a system for a central station, there being, as already stated in the beginning of this chapter, no absolute dividing line between the two. The selection of the best system for a central station is the most serious problem that

the electrical engineer is called upon to solve, and having once decided, it is almost impossible to change. If the business of the station is to be confined to arc lighting for streets, the constant-current series arc system would naturally be adopted. In such a case there would formerly have been little question, but Fifth Avenue in New York City is now lighted by arc lamps on the low-tension (230 volt, 3 wire) system; and the alternating current is used in many places for supplying arc lamps by means of transformers, the primary circuits of which are connected in parallel as usual, but the secondaries give a constant current, each feeding from 25 to 100 lamps in series. This system has the advantage that one generator can supply many circuits, whereas the direct-current series arcs require a separate machine (Chap. XVIII.) for each circuit. Furthermore, the same current can be used to feed incandescent lamps and motors through constant-potential transformers.

If the average distances of the lamps from the station are not very great, the low-tension direct-current system is very satisfactory for arc lamps, particularly if incandescent lamps are also supplied. But a large station usually does a general business, including arc and incandescent lighting and power distribution to various distances from the station; and the problem then becomes very complicated.

Alternating vs. Direct Current. — This brings us face to face with the much-discussed question of high-tension alternating *versus* low-tension direct current, concerning which there are radical differences of opinion among the best authorities. In both America and Europe, the greater number of incandescent lamps are now operated by the low-tension direct-current system; hence custom sanctions its use. But allowance should be made for the fact that the alternating current has not been so long in general use. The only reason for adopting high-voltage alternating or other currents in electric lighting is to reduce the cost of the conductors required. The cross-section of wire needed to convey a given amount of electrical power in watts, with a given percentage of "drop," or loss of potential in volts, is inversely proportional to the square of the *E.M.F.* employed. In other words, it requires a wire of only one-quarter of the cross-section and weight, if the voltage be made twice as great; hence the great economy in conductors secured by the use of high-tension currents.

This advantage can be realized either in saving the weight of wire required, or in transmitting the current to a great distance with the same weight of copper.

In comparing and deciding between the alternating- and the direct-current systems, there is a tendency to think only of the cost of the copper conductors, and to forget the cost of transformers, greater complication, and positive danger to human life, all of which ought to be counted against the high-tension alternating system. Furthermore, an electric-light plant usually runs a large part of the time lightly loaded; and during all that time the alternating system is much more wasteful of energy than the direct; because in the former case the leakage current is always flowing in the transformers, whereas, in a direct-current system the loss of energy in the distribution system is extremely small at light load, since it varies as the square of the current. If the distances of the lamps are very great, — several miles, for example, — then, however, there is little or no question, and an alternating-current system with transformers would almost necessarily be adopted. Formerly, in this country, the potential was almost always 1,000 volts; but now 2,000 volts, or more, are generally used, which still further extends the distance at which lamps can be economically operated. By the use of potentials of 20,000 to 60,000 volts, or even higher pressures, obtained by "step-up" transformers, the possible distance may become 20 to 100 miles or almost any distance, the chief limitation being the question of economy. If, on the other hand, the population is fairly large and dense, so that a sufficient number of customers can be found within about 1½ mile of the station, then, for the reasons stated above, a low-tension direct system is usually more satisfactory.

The limit of distance at which the alternating system is preferable to the direct cannot be fixed exactly, since it depends upon so many factors, one of which, for example, is *the value of human life*. Prof. J. A. Fleming states that the economical limits are reached in the two-wire direct-current system (about 110 volts) "when the mean length of the feeders is some 300 or 400 yards;" and in the three-wire system (about 220 volts) "when the mean length of the feeders is from half to three-quarters of a mile" (*The Alternating Current Transformer*, vol. ii., p. 337). With a mean length of feeder of ¾ mile, lamps can be fed at a distance

of 1½ mile from the station, which makes it possible to supply a circular district three miles in diameter, if the station is at the center; if it is not at the center, the available district will be correspondingly smaller. Other parts of the city can be lighted by other central stations, or by sub-stations. By operating the three-wire system with 220-volt lamps, a total pressure of 440 volts is obtained and twice the distance may be reached with the same power, weight of copper, and percentage of drop in voltage. For the same distance the weight of copper is only one-quarter as great, as stated on page 43. It is also possible by certain other methods to extend considerably the economical limit of distance. One plan is to generate a higher electrical pressure at the station, to supply those lamps which are remote; that is, the feeders running to the most distant parts of the district are operated at a higher voltage than the others. This higher pressure is produced by special dynamos, or, more conveniently, by small auxiliary dynamos, called "boosters," which raise the voltage in certain feeders. These various arrangements are described in Chapters III. and IV. of Volume II.

A method adopted in many of the largest and most modern electric-light and power (including electric-railway) systems combines the advantages of high-potential alternating-current transmission and low-potential direct-current distribution. Three-phase currents, usually at 6,600 volts, are produced directly by the generators, no step-up transformers being required. This energy is carried in most cases by underground, three-conductor cables to sub-stations where it is stepped down by transformers to six-phase currents at about 165 volts. Rotary converters change this energy into direct current at about 270 volts, which is fed to the outside conductors of the three-wire system that supplies the lamps, motors, etc. A drop of 40 or 50 volts is allowed on the feeders, mains, and wiring, so that 220 or 230 volts are actually delivered; that is, 110 or 115 volts on each side of the three-wire system.

Many large as well as small electric-light and power corporations use two- or three-phase currents without conversion to direct current.

With high voltage and transformers almost any distance may be reached. On the other hand storage batteries or other electrolytic apparatus cannot be operated and variable speed motors do not work as well. These various methods of distribution are described in Chapter X. of Volume II.

CHAPTER V.

THE LOCATION AND GENERAL ARRANGEMENT OF ELECTRIC-LIGHTING PLANTS.

To determine the location of an electric-lighting plant is often a matter of great difficulty, owing to the fact that so many considerations are involved, the most prominent of which are the following: —

1. Kind of power used (water or steam).
2. State and municipal laws and insurance rules and rates.
3. Size, form, and character of the district and distribution of lamps to be lighted.
4. Cost of ground space.
5. Room for extension.
6. Convenience of coal supply.
7. Convenience of water supply for boilers and condensers.
8. Possibility of obtaining good foundations.
9. Possibility of obtaining good chimney draught.

The kind of power adopted may absolutely determine the location of a plant, when, for example, a certain water power is to be employed that is only available at a certain point. In fact, if a water power of proper amount, reliability, and proximity exists, it would naturally be used wherever electric lighting is required, and the generating-plant would be put close to it.

If steam power be adopted, the location of the plant is not so limited; but even in that case it is necessary to carefully consider question of coal and water supply, which will be discussed under those headings.

State and municipal laws, iusurance rules and rates in some cases determine or affect the location of the station. For example, if a high-tension current were forbidden by law, then it would be necessary to locate the station in or near the district to be lighted. On the other hand, if it were not permissible to locate a station in a city on account of objection to smoke or vibration, then the station would have to be put outside of the

city limits, and a high-tension transformer system employed. These matters depend entirely upon local law and custom, and no general rules can be laid down. Ordinarily, however, one is permitted to locate a station within the city if he desires to do so. But it is well to choose a site surrounded by factories, stables, etc., the owners or occupants of which are not likely to claim damages for smoke or vibration nuisance. A station situated among fine residences, for example, would almost certainly have serious trouble on this account, and a little discretion in this matter might save much annoyance and litigation.

The size, form, and character of the district to be lighted is to be determined by general circumstances, verified by a careful study and canvass to ascertain as definitely as possible the location and number of lights likely to be required, and the purposes for which they are to be used.

It is well to make an accurate map or plan showing these facts, which would be useful, not only in locating the station, but also in determining the amount of apparatus, conductors, etc., required; also in making financial calculations. The purpose for which lamps are used is important, since it indicates when and for how long they will be lighted. For example, butcher and dry-goods shops usually close early in the evening, whereas restaurants and saloons are open late. Professor E. P. Roberts has gone into this matter in detail, and tabulated what may be expected of different kinds of customers.* By adding up in this way the total number of lights that will probably be burning each hour of the day and night, it is possible to predetermine the load diagram or curve showing the current used at each hour, which would be of the greatest value in designing the plant. A certain amount of selection can be made in regard to the location and business of the customers, in order to improve the form of the district or the load diagram; but, of course, a company usually takes all the business that is obtainable, particularly in the beginning.

Mr. Hordern, in London *Lightning* of April 14, 1894, gives diagrams for the different classes of customers of the Westminster station, which show, however, that in practice it is very difficult to forecast a new customer's bill.

* "The Design of a Central Station for Incandescent Lights." *Electrical World*, N.Y., March 25 and April 22, 1893.

Having ascertained or estimated the number and distribution of the lamps, and, therefore, the size and form of the district, the next step would naturally be the determination of the exact location of the station.

This order of procedure might, however, be reversed, as the location of the station may be fixed by certain local circumstances, and then the size and form of the district to be lighted would be determined by the position of the station. In either case the ideal arrangement would, of course, be that in which the district was a perfect circle, with the station located at the center. Theoretically, the station should be located at what might be called the center of gravity of the system, determined by giving each part of the district a value proportional to the number of lamps to be supplied. This could be applied to any district, however irregular in form; but this ideal position would rarely be realized in practice, and a slight or even considerable departure from it would not be objectionable. Low-tension systems, however, that is, incandescent lighting systems employing 100 to 250 volts, usually require the station to be placed somewhere near the center. Exceptions to this rule may be made for special reasons, and by the use of peculiar devices. For example, the system may be operated with a larger percentage of loss of potential on the conductors than is usually allowed, or part of the dynamos can be run at a higher voltage than the others, in order to supply lamps at a greater distance, or the current in certain of the feeders may be raised in voltage by auxiliary dynamos, commonly called "boosters." These methods are more fully discussed on page 39. By such means low-potential systems are successfully operated where the station is situated at a considerable distance from the center of the district, or even entirely outside of it. The combination of high-voltage transmission and low-voltage distribution described on page 39 enables the station or power-house to be placed the same as for high-potential.

In the case of high-tension systems the station can be located at some distance from the district to be lighted, or even many miles away. Indeed, the sole reason for employing high potentials for electric lighting is the fact that a given amount of electrical energy can be conveyed by much smaller wires if high-voltage currents be used. Assuming a certain amount of electrical

power in watts and a given *percentage* of loss in volts, the cross-section of conductor required is inversely proportional to the square of the number of volts. This ability to carry electrical energy over comparatively small wires to considerable distances permits the station to be located in almost any desired position, irrespective of the size, shape, and position of the lighting district, within reasonable limits. This applies to alternating incandescent lighting and to series arc lighting, or to any other system using currents of 1,000 volts or more. The advantage of being able to locate the station wherever it may be convenient to have it, is offset by two serious facts, as already stated.

First, the danger of killing persons and animals by contact with wires carrying high-voltage currents.

Second, the difficulty of insulating high-voltage currents. This serious question between high and low tension systems has been long, and somewhat fiercely, discussed by electrical engineers; but there is probably no general answer, and each system has its proper sphere of usefulness, depending upon circumstances.

The cost of ground space is in many cases a controlling condition. It may happen that the rent or cost of sufficient ground space may be so high as to preclude the placing of the station in or even near the district to be lighted. This would oblige the station to be put some distance away, where ground would be sufficiently cheap, in which case a high-tension system would have to be adopted. Thus the various parts of this problem are interdependent, and a change in one may affect the others.

A high value of real estate would also affect the arrangement of the station, giving rise to three or four essentially different types of station, depending upon the cost of the ground space. These arrangements of station will be considered on page 46. In most cases the cost of ground space and its effect upon the location of the station are quite definite and easily ascertained.

Room for extension should always be provided, because it has been the history of nearly all successful stations and plants that their business has rapidly and greatly increased, it being not uncommon for the number of lights to double each year for several years. Provision should, therefore, be made to enable the plant to be enlarged to at least twice, and perhaps four or six times, its original size. All the land need not be obtained in

the first place, provided it can surely be had at a reasonable price when required.

The convenience of coal supply should be carefully considered in locating electric-lighting plants, if steam-power is to be used. If possible, a site should be selected directly upon some railway, or sufficiently near to be connected by a branch track or siding; or directly upon the water front, so that coal vessels can be brought alongside, and in either of these cases the arrangement should be such that the coal can be directly unloaded from the cars or vessels into the bins from which the boilers are supplied. Rehandling of the coal should be avoided as far as possible; and if the coal can be made to move or discharge itself by gravity, so much the better. If, however, it is not possible to place the plant where coal can be obtained directly from railway or boat, then it should be located so that the carting or other handling of the coal involves the minimum trouble and expense. The possibility of the coal supply being temporarily cut off by severe snowstorms, floods, or strikes should also be considered in locating and arranging the plant.

Convenience of water supply should also be given careful attention. In cities the supply may usually be obtained from the city waterworks, in which case it may not be considered in locating the station. This would usually involve, however, a heavy water tax, and it might therefore pay, even in that case, to sink an artesian or other well, or obtain water from some other source. In small towns regular waterworks do not ordinarily exist, and the plant would have to depend upon wells or some other natural supply of water, such as a stream, pond, or lake. In the case of natural water supply the location of the plant would have to be made accordingly.

The water supply required in electric lighting may be of two kinds: First, that needed for the boilers; and second, water for condensation, if condensing engines be used. The first kind of water should be very pure, if possible, to avoid the deposition of scale and sediment in the boilers, which is most objectionable. The water for condensing need not, necessarily, be very pure either mechanically or chemically, if surface condensers are employed; in fact, salt water can be used, as in the case of marine engines. But even in condensers it is desirable to have

reasonably pure water, and therefore it is generally found expedient to secure an ample supply of good water for both purposes; or, to put it another way, it would not pay to use condensing engines unless a good and sufficient supply of condensing water can be relied upon. Water supply for boilers and condensers is discussed in Chapter IX.

The possibility of obtaining good foundations is too serious a matter to be neglected in locating electric-light plants, because the machinery used is very heavy, and it should be substantially and firmly placed, in order to work steadily and properly. A careful investigation of the character of the ground should be made, to be sure of having solid foundations, as it might happen that the existence of soft ground or quicksand would involve great trouble and expense.

The matter of transmitting vibrations from machinery to adjacent buildings should be carefully considered, as it may be the cause of great annoyance, or even actual damage. This question is discussed in the next chapter, under the head of "Foundations."

The obtaining of a good draught for the boiler fires is another matter which must not be ignored in locating and arranging a plant. If natural draught by means of a chimney be adopted, two questions are involved: First, the foundations for a sufficiently high chimney must be particularly good, and even better than those for the building or machinery, because the slightest settling will throw the stack out of plumb, the effect being magnified by the height of the chimney; secondly, the formation of the land in the neighborhood of a chimney very considerably affects the draught. For example, if a chimney were located near a line of hills, and the prevailing winds happened to be from the hills toward the chimney, the effect would be to cause the wind to be deflected downward upon the chimney, which would tend to oppose the draught. In a case of this kind, or wherever natural draught is not to be obtained, it would be necessary to resort to mechanical draught of some kind.

Thus it will be seen that there are numerous important factors involved in determining the location of a station; and it is usually a great mistake to overlook any of them, or, on the other hand, to give undue weight to any particular one.

Location of Generating-Stations at Coal-Mines. — The possibility of locating large electrical generating-stations directly at coal-mines, and transmitting the energy by wires to the large cities for light, power, etc., has been proposed and discussed.* This is the extreme case of the location of a central station entirely with reference to coal supply. It is largely a question of whether it costs more to carry the coal or the electrical energy to the given point. The plan would have the enormous advantage of eliminating the serious evils due to excessive smoke in large cities, as well as the trouble and dirt involved in handling coal and ashes. Advanced civilization will probably demand it in the future; but railways and other established interests would combat it, and it is doubtful if the times are quite ripe for attempting it, except in places where the conditions are particularly favorable. A compromise scheme has been proposed by the author † in which the station would be located at a sufficient distance from the city to avoid the nuisance of smoke and dirt, and also reduce the handling of the coal. For example, a large station located in New Jersey could supply New York City, and would secure great saving in cost of land, coal, labor, etc.

ARRANGEMENT OF AN ELECTRIC-LIGHTING PLANT.

The general arrangement of an electric-lighting plant or station depends upon its location and the kind of machinery adopted.

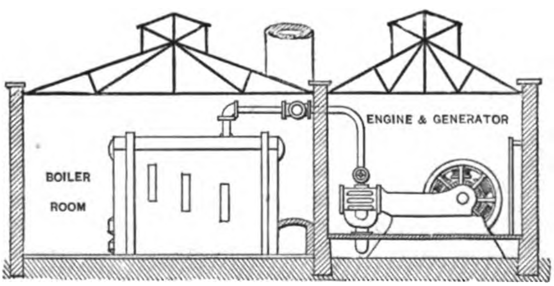


Fig. 1. Simple Arrangement of Plant.

The location of the station, particularly with reference to the value of real estate, gives rise to several radically different arrangements. If the cost of ground-space is low, and there is ample

* "Generating Power at Coal Fields and Transmitting it Electrically to Industrial Centres," *Elec. World*, Dec. 31, 1892. "The Utilization of Coal Mines." Professor Blake. *Sci. Amer. Sup.*, July 8, 1893.

† "Coalless Cities," *Cassier's Mag.*, December, 1895.

room, the simplest, and usually the best, arrangement is that shown in Fig. 1, in which the boilers, engines, and dynamos are all placed on the ground, the relative position being such that the steam flows directly from the boilers to the engines with a minimum length of pipe. This arrangement is natural and desirable in every way.

If, however, the cost of sufficient ground-space is too great to allow this plan to be followed, then it obviously becomes necessary to place some of the apparatus above the rest; that is, we must have a building with two or more stories.

In the first large electric-lighting central station built in the world — the Pearl-street Station of the Edison Electric Illuminating Company of New York, which began running in 1882 — this problem was solved by placing the boilers on the ground, the engines and dynamos, which were direct-coupled, being located on the floor above, which consisted of iron beams supported on iron columns. This arrangement was a natural one, but did not work satisfactorily, and is probably radically wrong, for the reason that the tendency of steam-engines to vibrate because of their reciprocating motion makes it practically imperative to place an engine of any size upon a solid foundation directly on the ground.

Boilers, on the other hand, although heavy, do not tend to cause vibration, and simply require a sufficiently strong support to carry the dead weight. The arrangement adopted, therefore, in many of the modern stations has been to place the boilers upon the second or even third story and locate the engines and dynamos on the ground. A prominent example of this arrangement is the Waterside Station of the New York Edison Co., which supplies a large part of Manhattan Island with electric light and power, having a maximum capacity of 160,000 H.P. It is shown in vertical section and plan in Figs. 2 and 3 respectively. The ground space covered is 197½ by 272½ feet, and the roof of the engine-room is 116 feet above the floor. A little less than one-half of the building is shown in the plan, but the remainder being precisely similar, the arrangement of the plant can be clearly seen. There are 16 generators, which produce three-phase alternating current at 25 cycles per second and 6,600 volts, and have a capacity of 4,500 K.W. each. The high-potential current thus generated is carried by underground cables to substations in various parts of the city, where it is stepped down in voltage and

converted into direct current to feed the three-wire network which supplies lamps, motors, etc., as already described on page 39. Each generator is directly connected to a vertical, compound engine. The boilers, 56 in number, are placed on two floors, as shown in

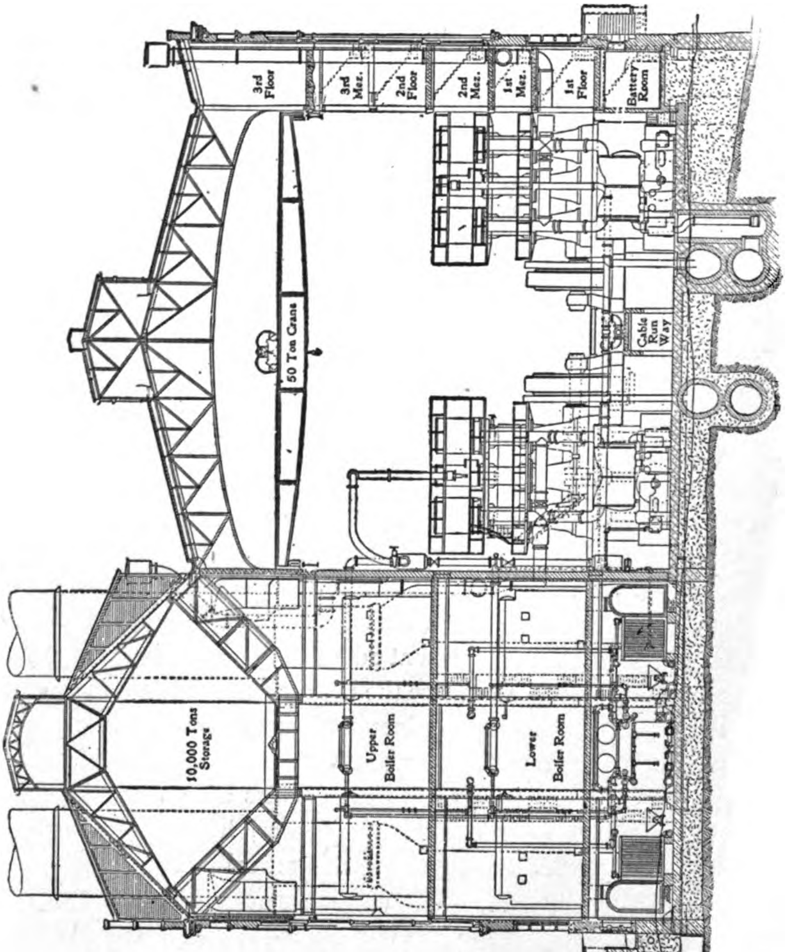


Fig. 2. Cross-section of Waterside Station, New York Edison Company.

Fig. 2, and above them is a coal-bunker having a capacity of 10,000 tons. It will be observed that the whole arrangement is designed to save ground space and yet not sacrifice effectiveness, economy, and convenience of operation. The steam-piping system of this plant is shown on page 117.

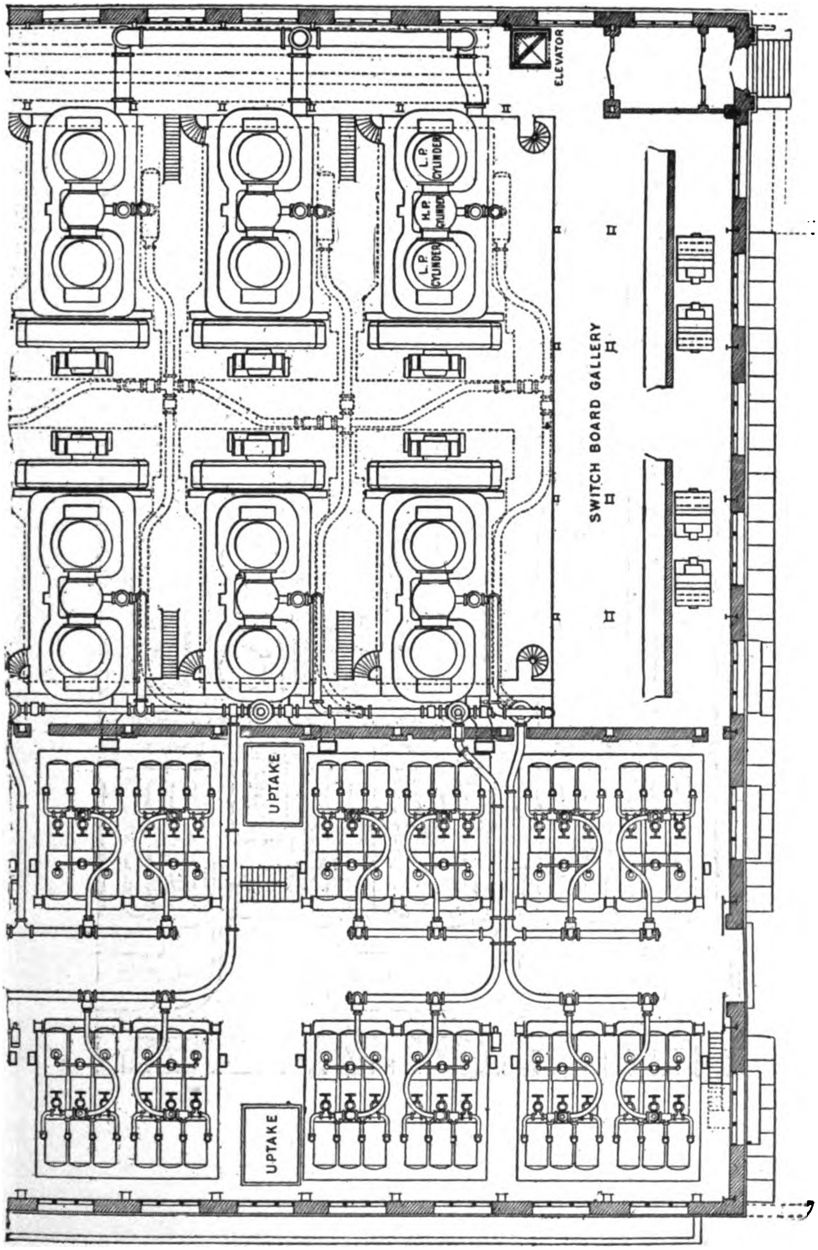


Fig. 3. **Portion of Plan of Waterside Station, New York Edison Company,**

In most of the electric-light plants built from the beginning in 1878 to about 1890, the dynamos were comparatively small—20 to 100 H.P.—and belted to the engines. One plan was to have each machine or pair of machines driven by a separate high-speed engine.

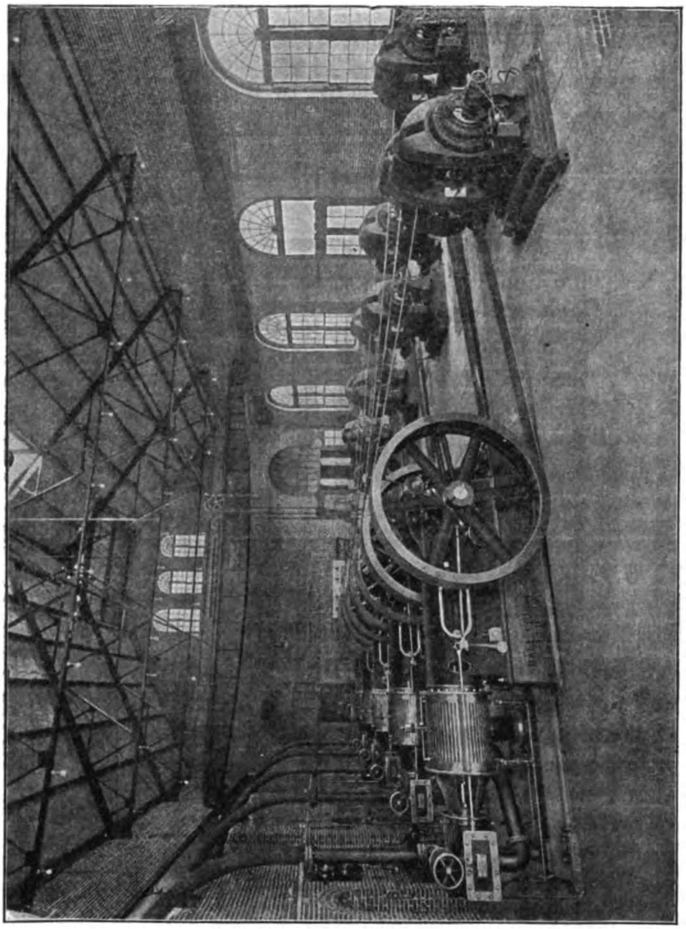


Fig. 4. Typical Direct-current Arc-lighting Station.

The other method was to employ one or more large, low-speed engines which drove line-shafts by means of heavy belts, the various dynamo being also connected to the line-shafts by belting. These arrangements are still commonly used in direct-current arc-lighting plants, because for the most part they supply street lamps, the distances being considerable, so that the high-potential series system is adopted.

The constant-current dynamo (Chap. XVIII.) required in this case is limited to a capacity of about 100 or 150 lights, so that many machines are needed. A modern example of such a station is illustrated in Fig. 4, a pair of dynamos being belted to each high-speed, tandem-compound engine. The series alternating is usually preferable to the series direct-current system, because thousands of arc lamps may be operated by one generator if desired, and incandescent lamps as well as motors at the same time, as stated on page 37. In such a case the general type of station represented in Figs. 2 and 3 may be adopted.

For several years after the alternating current was introduced in 1887, its use was limited to incandescent lighting and the generators were comparatively small, a few hundred lights' capacity, and usually installed in arc-lighting stations so that incandescent lamps could also be supplied. The consequence was that they were driven by high-speed or low-speed engines with belting, like the arc machines in Fig. 4. But the great increase in size of alternating as well as direct-current generators has resulted in the general adoption of direct connection in place of belting. Hence the modern station for electric light or power, whether direct, single-phase, or polyphase current, usually employs multipolar generators of large diameter, each directly connected to a steam-engine or other prime mover.

The isolated plant has followed similar lines of development, and is in fact a small central station except that high-speed engines of the various types shown in Chapters XI., XV. and XVIII. are generally adopted.

CHAPTER VI.

BUILDINGS FOR ELECTRIC-LIGHT PLANTS.

THE building in which an electric-light plant is placed may be designed and built specially for it, or it may be a building already in existence, and built for some other purpose. In the case of a central station the plant usually occupies the entire building, or a large portion of it; whereas, an isolated plant occupies a comparatively small space in the cellar or basement. In any case, the problem of constructing or arranging the building or space comes under the head of architecture rather than of electrical engineering; but it is always very desirable that the electrical engineer should at least be consulted, and have the plan submitted to him. Frequently, however, this is totally disregarded, and the electrical engineer is given a certain place in which to put the machinery; and the result is likely to be very unsatisfactory to all concerned.

This unwise practice is particularly common in regard to isolated plants; and it is the rule, rather than the exception, for the architect to provide a certain room or space which he may arbitrarily think sufficient for the electric-lighting plant. Very often this space is too cramped, or of wrong shape, to allow the machinery to be properly put in. In most cases the difficulty could have been entirely avoided if the electrical engineer had been given an opportunity to make suggestions or modifications in regard to the original plans. The author has visited many plants in which this trouble was very apparent. In one instance the machinery was located in what was little better than a hole in the middle of the cellar, in which ventilation was practically impossible. The consequence was that in summer the temperature of this place often rose as high as 125° F., thus causing the dynamos to run very hot; in fact, their actual output was reduced to about one-half, because they could not generate any more current without being heated above 160° or 170° F., which is the maximum allowable temperature. The attendants were,

of course, thoroughly uncomfortable, and unable to work to advantage. In this case there was plenty of room at the front or back of the basement where windows or direct openings to the outside air could have been had. In many other cases a few feet, or even inches, too little space is provided for the proper arrangement of machinery, resulting in its always working badly. The amount of space required for an isolated plant depends upon the work that it has to do; but usually at least two dynamos and two engines should be installed, and therefore the room required would be 30 to 40 feet long and 20 feet wide, in case the engines are belted to the dynamos, and 25 feet long by 15 feet wide where direct-coupled engines and dynamos were employed. Typical arrangements of an isolated plant are set forth in Chapter XXV. The principal points to consider in providing a place for an isolated plant are,—sufficient space for proper arrangement of machinery; convenient handling of coal and ashes; light; ventilation; and freedom from excessive dampness.

In regard to the third point, it is obvious that daylight is preferable to any other, and is particularly needed for cleaning or repairing machinery; but it often happens that it is necessary to locate an isolated plant where only artificial light can be obtained, in which case electric lamps may be employed; but it is very important to have at least one or more gas-lights, or other independent lights, in case of accident to the electrical plant, at which time light would be urgently required.

The central station, as already stated, usually has a building of its own largely or entirely devoted to it. If the building is already erected, the duty of the electrical engineer is to arrange it to the best advantage. This will ordinarily require some modification, which should, of course, always be as little as possible, in order to save time and expense. As a usual thing central stations located in buildings originally intended for other purposes have not been very satisfactory. Numerous fires and a great deal of bad engineering can be attributed to this practice. Indeed, central stations have been particularly liable to fires, and this fact should always be borne in mind in designing and constructing the building. In the earlier days of electric lighting this use of second-hand buildings was quite common; but at the present time electric lighting is sufficiently definite and well-established to war-

rant the putting up of a building especially for the purpose, and this is now usually done. In this case the electrical engineer should be consulted in the design and construction of the building, although the details of the work and matters having little or nothing to do with the electrical plant had better be left to architects and builders; in fact, it would be the same mistake for the electrical engineer to interfere in these matters as for the architect to dictate in regard to the electrical machinery.

The space required for a central station depends upon the number and kind of lights to be supplied, and upon the character and arrangement of the machinery. The general arrangement of a station was discussed in the preceding chapter, and it would not be difficult to calculate the size and form of building required in any given case. Two things must be carefully considered, — first, the building must be adapted to the plant to be installed in the beginning; and second, it must be arranged so that enlargement can be made without disarranging or interfering with the plant already in existence. This is usually best secured by providing for expansion in one or two definite directions, the building being

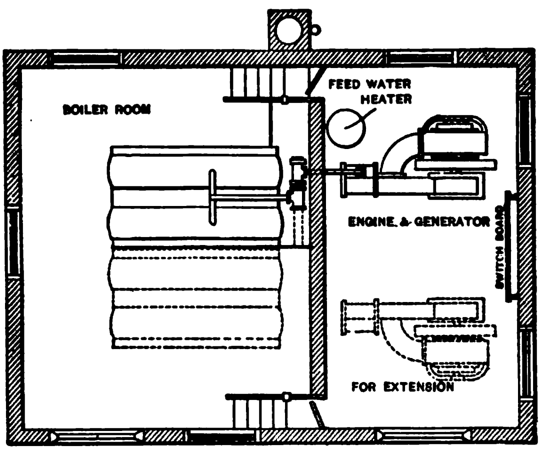


Fig. 5. Plan of Station Arranged for Extension.

extended and the machinery added, when needed, as shown in Fig. 5, a plan view corresponding to the vertical section in Fig. 1 on page 46.

It is customary to build electrical stations of wood and brick in a village or small town; of brick with a smaller amount of

wood for larger towns; and entirely of brick or stone, in order to to be more substantial and ornamental, in a large city.

Let us now briefly consider the foundation, walls, and other parts of the building, which, although not strictly a part of electrical engineering, nevertheless should be understood and considered by the electrical engineer in a general way.

FOUNDATIONS.

The foundation is the most important part of a building, according to Franklin, and this is particularly true of electric-lighting stations which contain heavy machinery. The electric-light engineer must therefore exercise the greatest care to secure substantial and enduring foundations. The particular kind of foundations will depend upon the character of the ground and other local conditions. Cases may occur varying from stations located on piles to stations which are set upon solid rock. Certain general engineering principles apply, however, to almost all cases, and are reasonably definite and reliable. Foundations should not be likely to be affected injuriously by frost, water, air, weather, or other mechanical or chemical action. Foundations may be displaced vertically by compression or settling of the ground, or horizontally by the sliding of the substrata on one another. Almost all foundations are liable to a slight amount of settling which may be perfectly legitimate; but any excessive or irregular settling of the different parts of the building is, of course, very objectionable. A careful investigation should, therefore, be made of the character of the ground by driving piles or iron tubes (ordinary gas-pipe), excavating, etc., to ascertain exactly what the ground will support, and what kind of foundation is required.

Foundations are either natural or artificial. The former are those in which there is solid rock or sufficiently substantial soil *in situ* to support the building without any reënforcement.

Artificial foundations are those in which piles, iron beams, caissons, or other special means are employed to reënforce soil which is not sufficiently firm itself.

The drainage of foundation should be carefully attended to. Means should be provided to free the foundation, excavation, and trenches from water accumulations, either by connections to

the regular town drainage system, or by temporary outlets, pumps, etc. It is better to divert springs and water channels, than to attempt to dam them away from foundations; because the latter requires a perfectly impervious wall, which is difficult to make and is likely to crack. The foundation for any important structure should be carefully tested, as already stated, by driving piles, digging deep pits at various points of the foundation site, or by augur boring, which brings up samples of the various soils it passes through. An actual test of the foundation soil may be made by applying to a certain portion of the ground a certain weight per square foot, corresponding to the weight of the building, etc., to be carried. In addition to these tests, one may be guided by the general data of the safe bearing-power of soils, etc., the values for which have been obtained by experience. These are given in the following table:—

HARD ROCK, in thick strata, can carry 200 tons per square foot.
GRAVEL AND COARSE SAND, well cemented with clay, protected from water, 4 to 8 tons.
SAND, compact and not liable to lateral disturbance, 4 to 8 tons.
SAND, clean, dry, 2 to 4 tons.
CLAY, in thick beds, always dry, 4 to 6 tons.
CLAY, moderately dry, 2 to 4 tons.
CLAY, soft, from 1 to 1.5 tons.
QUICKSAND, alluvial soil, etc., according to dampness, .5 to 1 ton.

Mud, quicksand, and other semi-liquid soils will, according to Rankine,* support per unit of area a weight equal to $wh\left(\frac{1+\sin a}{1-\sin a}\right)^2$, in which w is the weight of a unit volume of soil, h is the depth of immersion, and a is the angle of repose of the soil. It is not wise, however, to rely much upon the bearing-power of such soils; and it is better either to remove them entirely, to sink piles or caissons through them to a solid substratum, or to consolidate the soil by adding sand, earth, or stone.

In case the ground is so soft or unreliable as to require the driving of piles, these may be of hemlock, spruce, oak, yellow pine, or other suitable and available wood, perfectly straight and round, 30 to 40 feet long, and not less than 10 inches diameter at the smaller end, and 14 inches at the larger. Piles should be driven

* Rankine's *Civil Engineering*, p. 379.

perfectly vertically, and after being driven should have their heads sawed off squarely to a uniform height. This level should be below the lowest point at which the water in the soil is known to stand; otherwise the heads of the piles will quickly rot where they project above the water-level. Piles should be capped with a timber "crib," on which rest the foundation stones. This crib usually consists of 12×12 inch spruce or yellow pine, placed longitudinally, and treenailed to the piles, the space between the caps being filled with concrete.

Rankine's formula for the supporting-power of piles is:—

$$P = \sqrt{\frac{4\,Whse}{l} + \frac{4\,d^2s^2e^2}{l^2}} - \frac{2\,dse}{l},$$

in which P is total supporting-power in tons, W is weight of pile-driver ram in tons, h is height of fall in feet, s is section of pile in square feet, e is coefficient of elasticity of pile in tons per square foot, l is length of pile in feet, and d is distance in feet that the pile is moved by the last blow. A factor of safety of from 5 to 10 should be allowed in using the above formula.

Metal piles made of wrought or cast iron are sometimes used.

Excavating.—It is well to excavate the entire space under the engine-room to a depth of 8 or 10 feet, so as to get clear head-room in the basement. Excavate for all side, cross, and gable walls, all foundations, and also central space between boilers to form a basement under the boiler-room for ash and coal handling apparatus, flues, and pipes. The excavated material usually increases considerably in bulk, ordinary earth occupying about one-quarter more space, rock about one-half more; but loose soils may actually compress into less space than occupied in their natural position. Excavating is measured and priced by the cubic yard, and the ordinary single cart-load is equal to one cubic yard. The cost of excavating depends upon the hardness of the soil and depth of excavation, etc. The maximum distance that material can be thrown up with a shovel is 6 feet; hence, for greater depth, intermediate staging, or levels, must be provided, or the material must be carted out on an incline, or else hoisted. In loose ground a man can shovel about 10 cubic yards per day of 10 working-hours; in stiff clay or firm gravel, about 6 yards; in hard ground, where picking is required, 4 yards. One man can

remove 10 cubic yards to a distance of 20 yards, by means of a wheelbarrow, in one day. In excavating in compact soil, the sides are supported by short rough boards called "poling-boards," which are laid vertically against the sides, at intervals, and kept in place by cross-struts of timber.

If the excavation be a cellar, the sides must be sustained by inclined "shores" footed upon the excavated bottom. In very loose soil, long poling-boards are placed horizontally close together, and usually held in place by short vertical wales of stout plank and struts of timber across the trench. Excavations should be 6 inches wider on each side than the width of the foundation base, and the bottom should be made perfectly level; or, if on rising ground, in as long benches or steps as the gradient will allow. Trenches should be 3 feet wide if 8 or 9 feet deep, and 4 feet wide if over 9 feet deep.

Underfooting. — Foundation trenches are sometimes filled to a depth of 2 feet or more with broken stone, gravel, sand, and concrete, well rammed in convenient layers. This greatly increases the bearing-strength of the soil. When concrete is used, it should be made of good hard-setting lime, or hydraulic cement, so that it may act as a monolithic structure, in order to distribute the pressure over its whole area.

Foundation Footings. — The base or footing of the foundation projects considerably beyond the walls themselves, in order to distribute the pressure over a greater area. The following points should be taken into consideration: —

1. The area should be sufficient to impose upon the subsoil a pressure which it will safely bear per unit of area.

2. The foundation should support its load at or near its center.

3. The upper surface should be made horizontal in one plane, if possible, or in benches on rising ground.

Three kinds of foundation are employed: —

1. Those in which the foundation is of uniform width.

2. Those in which the foundation is wide where piers or pilasters occur, and narrow between them where the load is much less.

3. Those which consist of isolated parts not connected with each other. In this last case the excavation consists of pits instead of trenches.

In ordinary practice the footing-courses, upon which the walls of the building proper rest, consist of blocks or slabs of stone as large as are available and convenient to handle. Footings of brick or concrete are also used in very soft soils; footings consisting of timber-grillage are often employed. A grillage of iron or steel beams has also been used successfully. The inclination or angle, *a* (Fig. 6), of footing should be about as follows:

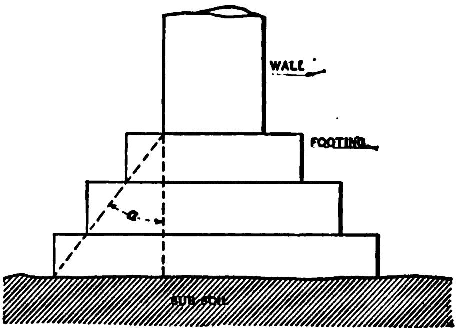


Fig. 6. Angle for Foundation Footing.

For metal footings 75°, for stone 60°, for concrete 45°, and for brick 30°. Damp-proof courses of slate, or layers of asphalt, are laid in or on the foundations or lower walls to prevent moisture arising or penetrating by capillary action.

The foundations for the machinery should be entirely separate from those of the walls and other parts of the building. The question of foundations for machinery is particularly troublesome, because it involves the problem of preventing the transmission of vibrations to adjoining rooms or buildings. Electrical machinery, and the engines, shafting, etc., used in connection with it, usually run at a high speed; and this fact aggravates the vibration. The character of the ground upon which the foundations rest determines how far and how intensely the vibrations are conveyed. Sand or soft earth transmits them poorly; firm earths transmit quite well, and rock almost perfectly. In cases where vibrations are likely to be transmitted and cause annoyance, various materials have been used to deaden them, such as sand, wood, hair-felt, mineral wool, and asphaltic concrete. In rock or firm earth one plan is to excavate a pit two or three feet deeper and two or three feet wider on all sides than the foundations are intended to be.

A bed of the same thickness of sand is then put in the bottom, and the foundations are built upon this, and are filled around with sand. Another way is to lay foundations upon a crib of 2″ × 12″ wooden plank, and cap the foundations with timber; but wood transmits vibration too well to be very effective for deadening purposes. On solid rock, where there is great fear of transmitting vibrations, the rock may be excavated six feet deeper than the foundations, and filled in with hair-felt or mineral wool, upon which the foundation is built. The most satisfactory solution of this problem seems to be the use of bituminous or asphaltic con-

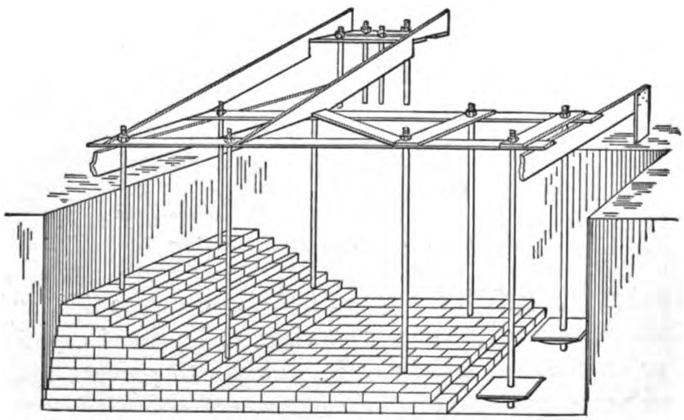


Fig. 7. Template for use in Building Machinery Foundations.

crete, which is made to form the lower one, or two feet of the foundations, the remainder being brickwork, or ordinary concrete with a bluestone cap. This has been extensively tried in France for steam-hammers, engines, dynamos, etc., with excellent results.

The machinery foundations themselves consist of a mass of brickwork, stone-masonry, or concrete, upon which the machinery is placed, the latter being usually held firmly in place by bolts passing entirely through the mass.

These bolts are built into the foundations, the proper positions for them being determined by a wooden frame or template, as indicated in Fig. 7. The brickwork for machinery foundations should consist of hard-burned bricks of first quality, laid in good cement-mortar. Ordinary lime-mortar is entirely unfit for the purpose, being likely to crumble away under the effect of the vibrations

caused by the machinery. Brick or concrete foundations should be finished with a cap or slab of bluestone. This tends to hold the foundations together, and also forms a level surface upon which to set the machinery. If the engine is self-contained, that is, provided with a cast-iron base, a stone cap for brick foundations may be dispensed with.

Walls.—The walls of the building may consist of either wood, brick, stone, or iron, depending upon its location, size, and other circumstances. The walls of a station in a small town were formerly built of wood in many cases, but present practice is to adopt brick or stone except, perhaps, for unimportant or temporary plants. Corrugated iron has also been used because it is cheap and fireproof, but is very unsatisfactory as it rusts out rapidly. A new fireproof construction consists of "expanded metal" (sheet iron with rough holes) supported on iron framework and covered with cement mortar outside and hard plaster inside.

A simple type of electric-light station, designed by Mr. C. J. H. Woodbury, is represented in Fig. 8. The right-hand side shows a wooden wall, and the left-hand side a brick wall construction. Brick walls should be at least 12 inches thick, even in small stations, and 16 or 20 inches thick in large ones. There may be a pilaster at each roof-truss, having 8 inches projection and 24 inch face, or the wall may be of uniform thickness if sufficiently heavy. More elaborate stations are shown in Figs. 2 and 3 and in Chapter XXV.

The bricks used should be hard-burned, and have clean, sharp edges, no salmon or light-colored brick being allowed.

The common size of bricks is about 8 by 3½ to 4 by 2 to 2½ inches, or about 24 per cubic foot (including mortar), and weighing about 4½ lbs., or 2¼ tons per thousand. A pressed brick of the same size will average about 5 lbs. each. The crushing strength of bricks varies greatly. A soft one will crush at about 500 or 1,000 lbs. per square inch, while a first-rate machine-pressed brick will not crush with less than 3,000 to 5,000 lbs. per square inch. Cracking and splitting, however, usually commence at about one-half the crushing load; and to be really safe the load should not exceed one-tenth of the crushing strength. Bricks may be laid in common lime mortar or cement mortar; the latter is much prefer-

able, particularly if the walls are subjected to vibration, or are required to carry considerable weight, in cases where machinery is put upon floors supported by the walls, or where traveling cranes are used. Common mortar consists of one part of quicklime and three to four parts of sand by bulk. About 20 cubic feet of mortar are sufficient to lay a thousand brick with coarse joints of ⅜ inch, usual in interior walls. In such cases one thousand brick make 2 cubic yards of massive work, nearly one-third of the volume being mortar. For outside or other joints which show,

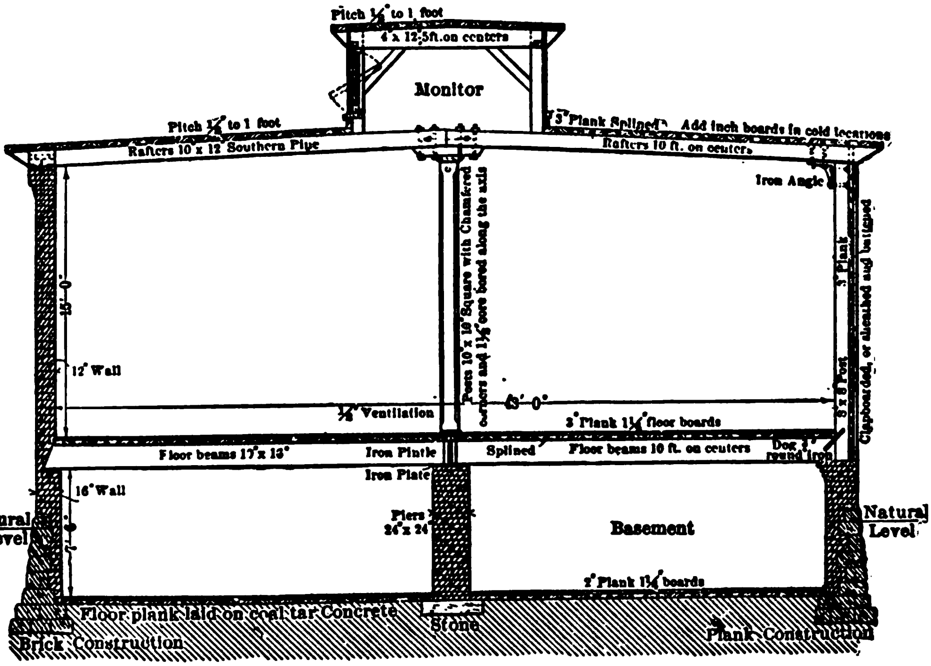


Fig. 8. Standard Electric-Light Station.

a whiter and thinner layer of mortar is used, made of one part of lime to 2½ or 3½ parts of sand. It is necessary to protect quicklime from moisture, as even the moisture of the air will cause it to undergo the process of air-slaking. The average weight of common hardened mortar is 105 to 115 lbs. per cubic foot. The crushing strength of good common mortar six months old is from 125 to 200 lbs. per square inch. Both the sand and lime of lime mortar should be free from clay and soil. Mortar should not be mixed upon the surface of clay ground; but a rough

board, brick, or stone platform should be interposed. Pit sand sifted is excellent for mortar. Its sharp angles make with the lime a more coherent mass than the rounded grains of river or sea sand, the latter also having the objection of containing salt, which is very difficult to remove. One barrel of unslaked lime (230 lbs.) will make about one cubic yard of ordinary mortar. Mortar should be applied wetter in hot than in cold weather.

As already stated, cement mortar is preferable to common mortar, when required to stand considerable weight or vibration. This consists of 1 part of cement and 2 to 4 parts of sand. It is very important that the cement and sand be thoroughly mixed.

A bricklayer and a laborer to keep him well supplied with materials will, in common house walls, lay an average of about 1,200 to 1,500 brick per day of 10 working hours; in good, ordinary street fronts 700 to 1,000, and on very fine work with angles, etc., 150 to 300. In plain massive engineering work he should average about 1,500 per day. Higher figures than these are sometimes given by engineering authorities, but it is doubtful if they can be realized. This may partly be accounted for by the fact that the working-day is now only 9 or even 8 hours, instead of 10, which was formerly the rule.

Brick with rounded corners may be used around the windows both at the sides and on the sill, also at the doorways. It gives a better finish and appearance.

Stone walls for stations are used in large cities where more substantial and ornamental structures are desired. The kind of stone employed for the purpose will depend upon what is most available, but would ordinarily be sandstone, limestone, or granite, laid in cement mortar. The cost of good stone masonry of course varies greatly, but is usually between $20 and $40 per cubic yard.

The most modern construction especially for large and important buildings consists of steel frames with an outer facing of stone or brick. It may be designed to carry any given weight, and the external appearance of the building may be made as fine and ornamental as desired.

Roofs.—The roof beams, or trusses which support the roof proper, may consist of either wood or iron, the former having the advantage of cheapness, the latter being stronger and fireproof.

The simple roof construction shown in Fig. 8, consisting of timbers 10 or 12 inches square and 10 feet between centers, will answer for small stations. For larger stations wooden roof trusses may be used, but steel trusses are generally worth the extra cost in order to reduce the fire risk. It is customary to have a louver or monitor, with side ventilators, as in Fig. 8. This may be omitted, however, if there is much danger from outside fires. Whether the trusses be of wood or iron, the roof itself may be made of 3-inch plank splined, having a proper pitch, and covered with slate, tin, or tar and gravel.

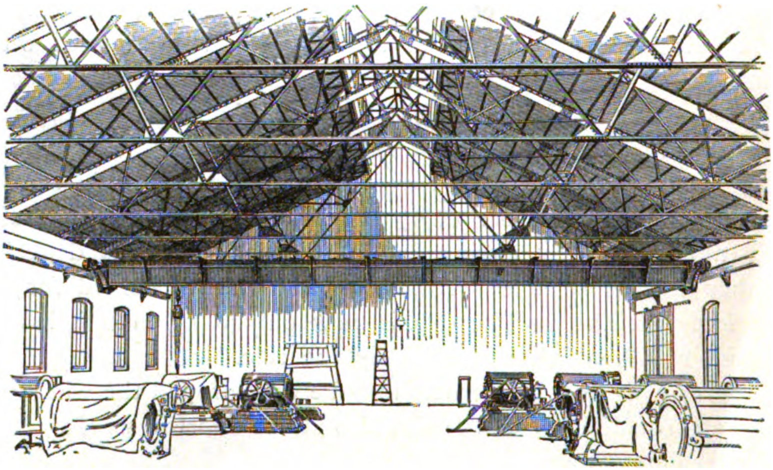


Fig. 9. Iron Roof Construction.

Since electrical stations have been particularly liable to fires, and since sprinklers are not usually desirable in them, it is well to make the roof fireproof by constructing it of terra-cotta blocks, tiles, or of cement-concrete with "expanded metal" as the tension member of the slab. A plank roof may be made almost fireproof by covering the under side with expanded metal and hard plaster. Examples of iron roof construction are given in Figs. 2, 4 and 9, which also show the travelling crane, a necessary element in plants of any size.

Floors.—The engine and dynamo room floor may consist of two layers of plank, the first of yellow or Norway pine splined, and the second of $\frac{7}{8}$-inch maple. The boards of the second floor should not be over 4 inches wide, and should be blind-nailed.

A brick or cement floor is sometimes considered undesirable for a room containing machinery, because the grit produced by wear is stirred up by walking or sweeping, thereby getting into the bearings and other parts of the machinery, and causing them to wear and heat. For that reason a wooden surface for the floor is generally provided in rooms containing running machinery. In the case of high-potential plants another reason advanced for using wooden, and not brick or cement, floors is the fact that the latter would be apt to cause a man standing on them to make electrical connection with the ground, and accidental contact with a dynamo or wire might injure or even kill him. In fact, where dangerously high voltages are generated, some special means should be carefully provided for securing perfect insulation of the floor in the neighborhood of dynamos, switchboards, and other places where men have to handle the high-tension apparatus. This may consist of rubber mats, or the floor may be made of boards or planks having the pores filled with oil, paraffine, or other substance to prevent absorption of moisture. These planks should be held by blind-nailing, or by driving the nail-heads below the surface three quarters of an inch or more, the holes being filled afterwards with wooden plugs, in order that persons may not, by accidental contact with the nails, be hurt. Where extremely high voltages are employed, a special insulated floor or platform mounted on glass or other insulators should be constructed. A well-insulated floor is the best safeguard against shocks to those working about high-potential machinery, and is well worth putting in, although it may not absolutely prevent such accidents.

The floor of the boiler-room should always be made of brick, concrete, cement or other suitable fireproof materials, because in this case there is not the same objection to grit and electrical conduction which may be urged against these materials when used for the floors of engine and dynamo rooms.

Division of Station Building.—In the station building space must be provided for the various parts of the plant and business as follows: The boiler-house may be a separate building, which in some respects is desirable to remove fire risk and dirt. In any case a brick wall or partition should be interposed between the boiler-room and the other parts of the building, in order to shut

off danger of fire; and this partition should be impervious without any direct opening into the engine and dynamo room, in order to exclude dirt and grit. If a doorway is needed, the door should be of the self-closing, tin-clad, fireproof type.

In or near the boiler-room, space must be provided for the coal, ashes, pumps, heaters, etc.; and it is important that this space should be suitably and conveniently arranged, the pumps, for example, being put in a separate room. To provide against interruption of coal supply by strikes or snow-storms it is very important to have ample storage capacity. This may consist of bins in the station (Fig. 2) or near by. Conveyers and other facilities for handling the coal and ashes should also be installed. The engines and generators, being the most valuable, delicate, and important parts of the plant, should have ample space, suitably located and arranged. Facilities should be provided for handling the machinery conveniently, the best plan being to have travelling cranes as in Figs. 2 and 4. There should be rooms for the various officers, clerks and other employees. Supply and storage rooms are needed, as well as repair shops for both metal and wood work.

In case overhead wires are used to distribute the current, a wire tower may be built on top of the building, usually at one end or corner. If the current is distributed by underground conductors, a cable-room should be arranged where the conduits lead out of the building. If a storage battery be a part of the plant, a suitable room must be provided for it, shut off as far as possible from the machinery and instruments, in order that the fumes from the battery may not corrode them. Several small rooms are usually needed for testing and adjusting lamps, meters, measuring-instruments, etc., the number and size of these depending upon the character and magnitude of the business.

All these different rooms and departments should be carefully considered and provided for in the original plans. It is not wise to build what appears to be a sufficiently large structure, and then try to fit in the various rooms and spaces afterwards.

In many cases the wires are brought in directly through a portion of the wall of the building. This matter has been discussed by C. E. Skinner and others.*

* Trans. Amer. Inst. Elec. Eng., July, 1903.

Stairs and Elevators should be placed outside where possible, or, if inside the building, stairs should be completely partitioned off from the room below with brick or hard wood, and provided with self-closing doors, hung at the bottom of the flight. Elevators should be completely partitioned off by brick walls, or not incased at all, but provided with approved self-closing hatches.

Inside Finish. — There should be as little as possible extra inside finish, such as sheathing, lath, plaster, etc., that would leave concealed places, or add inflammable material to the station. If the building be of brick, the inside should be left perfectly plain, or finished with paint to cover the roughness. If constructed of wood, the timbers and boarding should be dressed on the inside, if a rough finish is undesirable.

It is better to leave the inside walls and ceilings plain and open, and sacrifice appearance for safety against fire, which central stations seem to have been particularly liable to. The use of tiles on the interior walls, which is quite common in English and Continental stations, gives a finish which is excellent in appearance and cleanliness; but it would ordinarily be looked upon as an extravagance in this country, where first cost is considered so important.

Fire Doors and Shutters may be made of two thicknesses of one-inch matched boards, with a layer of asbestus between, and nailed together with French nails. The boards should run diagonally, the two sides in opposite directions, to give strength. The covering should be tin, laid on with flat lock, securely nailed under the lap, covering both sides and edges completely. The frame or casing should be as securely tin-clad as the door or shutter, which should be provided with a strong latch, to hold it in place. These doors are claimed to be better than those entirely made of wrought iron, for the reason that they do not warp so much when heated. Fire doors and shutters of corrugated sheet iron are less likely to warp than flat plates, and are frequently employed.

Fire Apparatus. — Automatic sprinklers may be arranged about the building; but they would be rather objectionable in the dynamo or supply rooms, as any drip from them would cause serious injury: but hydrants, pumps, fire-hose, and fire-buckets, the last being kept full of water, should be provided in stations

to an extent corresponding to the importance of the station, and the danger of fire.

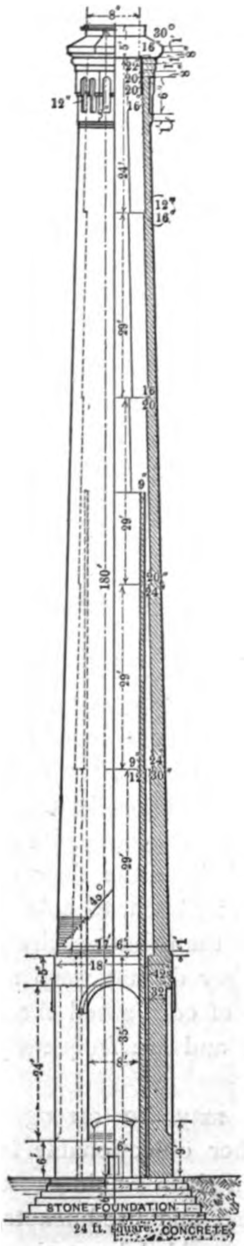


Fig. 10. Brick Chimney.

The Chimney is usually a very prominent feature of an electric-light station, and its design and construction demand considerable engineering ability. Great difference of opinion exists as to the relative desirability of brick or iron smoke-stacks. The former is more substantial, architecturally better in appearance, and does not lose so much heat by radiation; but the latter is cheaper in first cost, occupies less space, does not require such extremely solid foundation, and is not so likely to crack and allow cold air to leak in as the former. A brick chimney should have two substantial walls, with an air-space between, in order to prevent the cooling and the cracking of the inner wall or flue proper.

The right side of Fig. 10 shows a section, and the left side an elevation, of a standard brick chimney, dimensions, etc. being given. The almost universal rule is that the external diameter of a brick chimney at the bottom should be at least one-tenth of the height, in order to give sufficient stability to resist wind-pressure. The "batter," or taper, of a brick chimney should be from $\frac{1}{8}$ to $\frac{1}{4}$ inch to the foot on each side. Iron stacks should be lined with brick throughout their entire height; and they are prevented from overturning by strong lugs and bolts at the bottom, and by stays or braces of iron rod fastened to an angle iron ring at two-thirds the height of the stack, and spreading in three or more directions at about an angle of 45° to the horizontal, being securely attached to suitable objects. Iron stacks must be kept

well painted, to prevent rust. In some cases self-supporting iron chimneys, consisting of sections bolted or rivetted together, have been used. These have the advantage of not requiring guys or braces of any kind. The height of chimney required for a central station or large isolated plant would be from 100 to 200 feet, depending upon the boiler-power. In the case of small isolated plants, the chimney may merely form part of the walls of the building. For detail information of chimney design see Christie's "Chimney Design."

For further information regarding foundations, buildings, the interior arrangement of power plants, etc., the reader is referred to special treatises on the subject, such as:

Architectural Engineering, by J. K. FREITAG.

A Practical Treatise on Foundations, by W. M. PATTON.

Building Construction and Superintendence, by F. E. KIDDER.

Architecture of Central Stations, a paper read before the Royal Institute of British Architects, by C. S. PEACH, 1904.

Design of Steel Mill-Buildings, by M. S. KETCHUM.

Fire-Proofing of Steel Buildings, by J. K. FREITAG.

Central Electrical Stations, by C. H. WORDINGHAM.

Power-Station Design, by MERZ and MCLELLAN, a paper read before the Institution of Electrical Engineers, London, July, 1904.

CHAPTER VII.

POSSIBLE SOURCES OF ELECTRICAL ENERGY.

THE source from which to obtain electrical energy is obviously a matter of prime importance. It is, however, a most difficult problem, and one which is undergoing great change and progress at the present time. The difficulty of the problem is increased by the fact that it involves some of the deepest principles and finest points, not only in mechanical and electrical engineering, but also in chemistry, being, as it were, on the border-line between these great branches of applied science.

The interest and importance attached to this subject make it worth while, therefore, to carefully consider and compare the various methods of generating electricity, including not only those which are already in common and successful use, but also possible methods, even though they be not yet practical. These may be arranged as shown in the accompanying table: —

Possible Methods of Generating Electrical Energy.

Natural Sources of Energy.	Used in following apparatus.	Produce.	Used in following apparatus.	Produce.
Fuel, Including Coal, Oil, Natural Gas, Wood.	Voltaic battery, Metallurgical apparatus,	Electrical energy, Zinc or other metal,	Voltaic battery,	Electrical energy.
	Thermo-electric battery, Thermo-magnetic generator,	Electrical energy,		
Heat of Sun, **Heat of Earth,**	Steam-engine, Gas-engine, Hot-air engine,	Mechanical Energy.	Dynamo, Electrostatic machine.	Electrical energy.
Water Falls,	Water-wheel,			
Tides,	Water-wheel,			
Waves,	Wave-motor,			
Wind,	Windmill,			
Animal Power.	Treadmill or crank.			

This table shows the natural sources of energy that are at all available, all of which, with the exception of the power of the

tides and the internal heat of the earth, are derived from the radiant energy supplied to the earth by the sun. Of these possible sources only two—fuel and water-power—are now used to any extent to produce electrical energy, or, indeed, any other form of energy for any purpose requiring considerable power.

For various reasons, chiefly unreliability, the other sources are not very practical.

Animal-power can be used to generate electrical energy, as in the case of a small dynamo driven by hand; but the power is very small. Even a strong horse working in a treadmill could hardly drive a dynamo of sufficient capacity to supply ten ordinary incandescent lamps. In short, animal-power is obviously inadequate for heavy work.

Wind-power is cheap and simple; but it is proverbially unreliable and unsteady, and therefore requires the use of storage batteries and rather complicated automatic devices for connecting the windmill, dynamo, and storage battery. Another limitation is the fact that the power obtained is small. For example a wheel twenty feet in diameter develops less than one horse-power with a wind of sixteen miles per hour. This subject is treated further in Chapter XIV.

Wave-power is, of course, primarily derived from the wind, but it is not quite so unreliable or unsteady. There are, however, great difficulties in its use. It is not practicable to drive a dynamo directly by a wave-motor. One plan consists in operating a pump by the up-and-down motion of a buoy. The water from the pump is carried through a pipe to a reservoir on the shore. This supplies a water-motor which drives a dynamo. In another arrangement the water-motor and dynamo are mounted on the buoy and the water is pumped into a chamber under considerable air pressure, but it is difficult to protect the dynamo from moisture. Articles on this subject appeared in the "Electrical Engineer" (N. Y.) Nov. 25, 1897, and "Western Electrician" Sept. 7, 1901.

The power of the tides is really due to the energy of rotation of the earth on its axis; and, theoretically, any resistance to the flow of the tides produces an infinitesimal slowing down of the earth. Tide-power is almost the only natural power not derived from the sun, and is more practical than wave-power. The usual

way of obtaining it is to allow the water to run into a pond at high tide, and when the tide begins to run out, a gate automatically closes. When the water-level outside falls a sufficient amount, the water in the pond is allowed to flow out, and to operate a turbine-wheel which drives a dynamo.

This power is much less likely to fail than ordinary water-power, being nearly constant throughout the year, except that ice would be apt to cause trouble. The disadvantages are that the turbine can only be run twice in the twenty-four hours for about four hours each time, and the times of these periods change with each day. This would necessitate the use of a storage battery.

It is evident that this power is only available on the seacoast, and then only at places having a large rise and fall of tide, which must be at least 6 feet, and should be 10 or 12, since the average head is considerably less. It is not likely that this source of energy will ever be largely used except in certain localities for small amounts of power.

Water-power is, as already stated, one of the two great sources of power used for large and important work. It is very simple in principle, and involves no very difficult theoretical or practical questions. The evaporative action of the sun lifts up, so to speak, the water, which afterward condenses, and falls as rain upon the land; and in running to the sea in the form of rivers or streams it is capable of giving mechanical energy in proportion to its weight and the height through which it descends, by passing it through a turbine, or other form of water-wheel, which, in turn, drives a dynamo that generates electricity. Water-power possesses the advantages of simplicity and cheapness; but it has the disadvantage of liability to fail during droughts in summer, and is subject to troubles from ice and floods in winter and spring. Water-power is usually not so cheap as is supposed, largely because of its unreliability; and frequently steam-power is preferred, even where water-power is available. The amount and accessibility of water-power are somewhat limited; and, with the exception of Niagara Falls, most of the water-power in the thickly settled parts of America and Europe is already used.

For example, the water-power at Holyoke, Mass., Rochester, N.Y., and Paterson, N. J., which are about the largest in their

respective States, are already nearly all used. Some countries, like Switzerland, have more than enough for their needs; but others, like England, have but an insignificant fraction of what is required. The long-distance transmission of electrical energy from water-powers tends to overcome this limitation. But it is a fact that most of the power developed at Niagara is used locally for electro-chemical and other purposes. Coal is so cheap in Buffalo that steam power can be produced there about as economically as electric power can be generated at Niagara and transmitted even the short distance of twenty miles. On the Pacific coast or in other regions where coal costs more, power is transmitted long distances advantageously.

The Heat of the Sun is a source of energy of enormous quantity, the total heat received per annum from the sun by the earth being equivalent to the combustion of a layer of coal eight inches thick covering the entire surface of the globe. A large part of this heat is, however, intercepted by clouds and the atmosphere. Moreover, the heat requires concentration or accumulation in order to develop any considerable power, the average quantity of heat received per square yard upon a clear day being equal to about one horse-power. Ericsson and others have focussed the sun's heat by lenses or mirrors, and operated engines of a few horse-power. This source of energy has the insuperable difficulty of being interrupted by cloudy weather for weeks at a time. If this heat were employed to operate steam or other heat engines, the case would be very similar to the use of the heat obtained from fuel, which will be discussed later.

Heat of the Earth.—This is also a possible source of energy of vast quantity. It manifests itself naturally in the case of thermal springs, volcanoes, etc. It is made evident artificially in deep mines and oil-wells. A well near Leipsic, Germany, is 5,740 feet deep, and has a temperature of 135.5° F. at the bottom; and another at Wheeling, W. Va., is 4,500 feet deep, and has a temperature of 110.3° F. at the bottom.* In many other places, particularly near active or extinct volcanoes, the temperature would be much higher at a given depth. This cannot, however, be said to be a practical source of energy at

* See papers by Professor W. Hallock. *American Association for the Advancement of Science*, vol. xl., 1891, and vol. xlii, 1893; also *Cassier's Magazine*, Feb., 1903.

present; but it is by no means impossible that deep holes might be bored in favorable localities for the express purpose of obtaining heat from the earth. To obtain mechanical or electrical power from this heat would, as in the case of the sun's heat, be a matter similar to the utilization of the heat of fuel, which is the next subject to consider.

Fuel. — The use of fuel in the production of electrical energy is one of the most momentous and difficult problems presented to the human mind. Even a fairly satisfactory solution of it requires the employment of some of the most important principles in science and engineering, and has a very great effect upon civilization. A direct and satisfactory solution of this grand problem is the hope and aim of many of the greatest living men of science; and its probable effect would be to revolutionize present methods in agriculture, mining, manufacturing, commerce, and even domestic economy.

The energy in fuel exists in the form of chemical affinity; that is, the atoms of carbon and hydrogen of which it is composed have a very strong affinity for oxygen; and under proper conditions combination takes place, the chemical energy possessed by the fuel being converted into some other form of energy, usually that of heat. This energy in the fuel is latent or potential energy similar to that of a stretched spring, which is entirely inactive until it is released. In fact, carbon is one of the most inert of all substances at ordinary temperatures, and will exist without sensible action or change for centuries. This potential energy of fuel is stored in it by the action of the sun's rays upon plant-cells in which carbon dioxide is decomposed, carbonaceous material being formed and oxygen set free. This carbonaceous material can be used immediately as fuel, as in the case of wood; or it may be converted into peat, coal, etc., by long-continued natural processes.

The ordinary method of obtaining energy from fuel is that of combustion, which consists in causing the carbon to combine with the oxygen of the air, producing carbon dioxide again, and generating an enormous amount of energy in the form of heat. This combination does not ordinarily take place except at a high temperature, usually about a red heat, which is the condition necessary for the action.

Steam-Engines. — The heat energy produced by combustion can be applied in various ways to produce mechanical or electrical energy, the most common method being to cause it to evaporate water in a boiler, the steam produced being used in the cylinder of a steam-engine to move the piston and produce mechanical power. In the gas-engine the fuel in the form of gas (which may be either natural gas or some liquid or solid form of fuel previously converted into gas) is caused to combine with the oxygen of the air directly in the cylinder of a suitable machine, the combined gases being raised to a high pressure by the combustion, thereby actuating the engine. These and other similar forms of machine are called heat-engines; and with the exception of water-wheels they are practically the only prime-movers or original sources of power used for generating electrical energy or for any other useful purpose, and they have contributed more than any other factor to modern civilization.

Nevertheless, there are certain inherent theoretical and practical difficulties which apparently leave much room for radical improvement in the production of mechanical and electrical energy from fuel. In the first place, the method now ordinarily employed to generate electricity is very roundabout. It consists, first, in burning coal under a boiler; second, evaporating water in the boiler; third, conveying the steam to the cylinder of the engine; fourth, allowing the steam to expand and move the piston; fifth, transmitting the motion of the piston by means of mechanism to produce rotation of the shaft of the engine; sixth, causing the rotation of the dynamo by mechanical connection with the engine; seventh, generating electric currents in the dynamo by revolving conductors in a magnetic field. Thus we see that there are seven distinct steps in the process of generating electricity, for which three large and expensive pieces of apparatus are required; viz., boiler, steam-engine, and dynamo, each of which has a great many parts and requires considerable attention; and these three main pieces of apparatus have to be connected together by piping, mechanism, etc., which still further complicate the plant.

In addition to the very objectionable indirectness of the present method of generating electricity with the steam-engine and dynamo, there is a theoretical limitation to the efficiency of a

heat-engine which is still more serious. The greatest possible efficiency of any heat-engine is expressed by the formula $E = \frac{T_1 - T_2}{T_1}$, in which T_1 is the initial absolute temperature and T_2 the final absolute temperature. This formula is derived from the second law of thermo-dynamics, and signifies that if steam or hot gases enter the cylinder of a heat-engine, and begin to act at a temperature T_1, and cease to act and pass out at a temperature T_2, then the maximum possible efficiency of that engine is given by the formula. For example, an ordinary non-condensing engine receiving steam at 80 lbs. pressure, which is equivalent to a temperature of 162° C., and exhausting or giving out steam at the atmospheric pressure of 15 lbs., equivalent to 100° C., would have an efficiency

$$= \frac{(273 + 162) - (273 + 100)}{273 + 162} = 14\tfrac{1}{4} \text{ per cent.}$$

This efficiency is theoretical, and takes no account of friction, radiation of heat, cylinder condensation, and other losses, and must therefore be still further reduced in order to represent the actual or net efficiency given by the engine. These losses often amount to a large fraction of the total theoretical power of the engine. Assuming, therefore, that the theoretical efficiency of a given engine is 15 to 20 per cent, as calculated by the above formula, then the actual commercial efficiency will be in the neighborhood of 8 to 12 per cent. As a matter of fact, these figures are approximately the theoretical and actual efficiencies given by good steam-engines in ordinary practice. Another way to arrive at this same fact, and one which is more concrete, is to compare the actual consumption of coal per horse-power hour with the amount of coal that would be required if the entire energy were converted into mechanical work. The amount of heat-energy produced by the complete combustion of a pound of good coal is about 13,000 units (pound-Fahr.), equal to about 10,000,000 foot-pounds, which would give one horse-power for five hours; consequently the amount of coal required per horse-power hour is only .2 lb. The actual coal consumption in the best steam-engines is 1 to 2 lbs. per horse-power hour, and ordinary engines use 3 or 4 lbs., or even more; hence the real consumption of coal is five to twenty times the theoretical amount which would be required if all the

heat were converted into mechanical power. The simple reason why the theoretical efficiency of a heat-engine is ordinarily far below 100 per cent, even without taking account of friction, etc., is the fact that a great deal of the heat-energy of the steam or gas passes out of the cylinder in the exhaust, and is not converted into mechanical energy. It is analogous to the case of a water-wheel which only utilizes a small fraction of the total fall or head of water. This fact is clearly shown by the formula given above, in which T_2 represents the temperature of the out-going steam or gas. If this temperature were absolute zero ($-273°$ C.), then the efficiency would be 100 per cent. If, on the other hand, the temperature T_2 is considerably above absolute zero, then the efficiency is correspondingly reduced below 100 per cent. As a matter of fact, the temperature of the exhaust of non-condensing engines is at least 100° C., or 373° absolute; and in the case of condensing engines, T_2 is about 300° to 325° absolute. Now, it would not seem to be possible to reduce these temperatures further, for the simple reason that a non-condensing engine cannot have a temperature in the exhaust below boiling-point; and the temperature of water for condensation cannot be below freezing, and is usually considerably above that point. The inference would therefore be that the only practical method of improving the efficiency of a heat-engine is to raise the initial temperature of the steam or gas. In point of fact, this is the way that the efficiency of heat-engines has been, and is now being, increased. In the time of James Watt, very low steam-pressures were employed, usually about 5 or 10 lbs. per square inch; and before that time even lower pressures, of 2 or 3 lbs., were used. These low initial pressures, and therefore temperatures, necessarily meant low efficiency and large consumption of coal per horse-power hour. Since that time steam-pressures have been steadily and greatly increased, until we now have 150 or even 200 lbs. pressure in common use. Indeed, the principal improvement in the steam-engine during the last hundred years has been the increase of steam-pressure and the necessary strengthening and modification of the boilers, engines and steam piping to enable them to withstand these high pressures, which not only greatly augment the efficiency, but also produce much more power in the same size of engine.

Obviously great difficulties are encountered in largely increasing the pressure. In the case of the steam-boiler there are at least two serious obstacles, which are apparently inherent and almost insurmountable. The first of these is the fact that the thickness of the boiler, upon which its strength largely depends, cannot be very much increased without reducing the passage of heat through it, and without adding enormous weight and cost to the boiler, the surface required being large. There are also practical difficulties in the construction of a boiler of very thick metal. A still more serious difficulty is the fact that, as the pressure, and therefore temperature, of the steam are raised, a point is finally reached at which the strength of the boiler begins to be reduced by the heat, and would not permit further increase of pressure. The difficulty of lubrication at high temperatures is also a serious obstacle.

Gas-Engines.—In these respects the gas-engine may claim to possess great advantages over the steam-engine in its possible ultimate efficiency, for the reason that the high pressure and temperature are produced directly in the cylinder, which can be made of almost unlimited thickness, since it is comparatively small, and the heat does not have to be transmitted through its walls. In this way we entirely eliminate the steam-boiler, which is the chief limitation to the increase of steam-pressure. It cannot be said that the gas-engine has as yet realized all of this great advantage over the steam-engine. Nevertheless there are gas-engines working to-day that show theoretical and actual efficiencies considerably higher than those of the best steam-engines. (See table on p. 80.) Professor Unwin stated in his lecture before the Society of Arts, January, 1893, that gas-engines had already given a thermal efficiency twice that of large steam-engines. Professor Ewing* has pointed out that the theoretical efficiency of the gas-engine would be 87 per cent if the initial temperature were that of combustion, and the final temperature that of the ordinary atmosphere. Previous compression of the gas would, of course, be necessary, and all friction and other losses would have to be eliminated. Assuming, however, that these losses amount to one-half of the theoretical power of the engine, an actual efficiency of 43½ per cent could still be obtained, which would be about four times the net efficiency of the best

* Article on "Steam Engine," *Ency. Brit.*, 1887.

steam-engines of the present day. The present gas-engines still have several practical difficulties, and will have to be considerably improved before very high efficiencies can be secured; but they possess the possibility of efficiencies much greater than those of the steam-engine. To show that a very high efficiency is not entirely visionary, we can refer to the cannon, which is really a gas-engine, since it converts heat-energy into mechanical energy. Professor Thurston states that a cannon actually has a thermodynamic efficiency of about 50 per cent.*

The hot-air engine has been developed by Ericsson and others, but is too far inferior to the steam- or gas-engine in efficiency and output to be used where more than a fraction of a horse-power is needed.

The remarkable increase in economy which has been secured during the last few years by the use of compound, triple-expansion, and quadruple-expansion steam-engines for both marine and land work, might lead one to imagine that this improvement can be carried on almost indefinitely. As a matter of fact, however, compound engines are just as surely limited in their theoretical efficiency as the simple engine. Their efficiency depends upon the initial and final temperatures of the steam as expressed by the formula discussed above, just as truly as in the case of any other heat-engine. The greater economy of compound engines is largely due to the reduction of cylinder condensation by avoiding large ranges of temperature in any one cylinder. This simply means that the simple engine would have larger losses, and its actual efficiency would be much less than the theoretical; whereas, in the case of a compound engine the actual efficiency would approximate more closely to the theoretical. Compound engines thus enable higher pressures to be used without having the great losses due to cylinder condensation which would occur in simple engines. It has been shown above, however, that apparently there are practical limits to the increase of the initial temperature; and it is a fact that even if the boiler could be kept at a red heat, the theoretical efficiency of the steam-engine would only be about 60 per cent, and the actual efficiency of course considerably lower.

The substitution of other fluids for water in boilers and engines

* *Science*, Oct. 31, 1891.

is one of the methods employed to secure higher efficiency. For example, some volatile liquid, like carbon bisulphide or sulphur dioxide, is used instead of, or supplementary to, water. This introduces difficulties, however, and does not greatly increase the efficiency, because the final temperature is not materially lowered.

The efficiencies of various steam- and gas-engines are compared in the following table given by Professor R. C. Carpenter.

STEAM-ENGINE AND GAS-ENGINE EFFICIENCIES.

Kind of Engine.	Coal per H. P.-hour.	Efficiency per cent.
Simple, non-condensing steam-engine	4 to 5	5.8 to 4.8
Compound, condensing, slide-valve steam-engine	8	7.1
" " Corliss "	2 to 2.5	10.6 to 8.5
Triple expansion, " "	$1\frac{3}{4}$ to 2	12.2 to 10.6
Quadruple " " "	$1\frac{1}{2}$ to $1\frac{3}{4}$	14.1 to 12.7
10 H. P. gas-engine		15
100 " " "		24
800 " " "		28

Direct Conversion of Fuel Energy.—The heat-engine, considered from all these points of view, does not seem to afford much encouragement for high efficiency in the conversion of fuel-energy into mechanical energy, except, perhaps, in the case of the gas-engine, which, however, still needs radical improvements. Moreover, in the generation of electrical energy the production of mechanical energy is merely a step, and the dynamo must be used to convert the mechanical into electrical energy; and although the dynamo is one of the most efficient and most perfect machines in existence, nevertheless our present method of producing electricity by means of a boiler, steam-engine, and dynamo is very indirect and complicated. The dream of the electrical engineer and scientist has therefore been to convert the energy of fuel directly into electrical energy, but as yet little or no practical progress has been made in this direction.

Thermo-electric Batteries.—It is possible to burn coal, gas, or other fuel, and use the heat produced, in a thermo-electric battery to generate electric currents directly. In simplicity this process is all that could be desired, since there is only one simple apparatus, without any moving parts, which is as harmless and easily taken care of as an ordinary stove, but unfortunately the efficiency is very low; in fact, it is limited by the same law as

the heat-engine, and is expressed by the same formula, $\frac{T_1 - T_2}{T_1}$, in which T_1 and T_2 are the temperatures of the ends of the elements. The possible differences of temperature between the ends would not seem to be so limited as the possible temperature of a steam-boiler. There are, however, many practical difficulties in maintaining one end of the elements at a very high temperature and the other end at a low temperature; and great trouble has been found in making perfect joints between dissimilar metals which would not crack after repeated heating and cooling.

Many persons think that there is an inherent deterioration of a thermo-electric battery which necessarily occurs after any considerable period of action. The author has made numerous experiments in connection with these batteries, and has seen some of them which have been in use several months almost continuously giving a fair output of .05 volt *external* potential difference, and 5 amperes per element ($1 \times 1 \times 4$ inches), without any apparent diminution in activity. There would seem to be no reason why there should be any such inevitable deterioration, beyond the fact that it is difficult to make a permanent joint between dissimilar metals, as already stated. This difficulty can be, in fact it has been, overcome by proper mechanical design and construction. The real difficulty is the low efficiency and small output of thermo-electric batteries. Probably the best results so far obtained do not give an efficiency over one or two per cent; that is, not more than one or two per cent of the heat-energy is converted into electrical energy, and probably the best output so far obtained is that stated above.

The Thermo-magnetic or Pyro-magnetic Generator has been experimented upon by Edison* and others. The action of this form of electric generator depends upon the fact that iron or nickel loses almost all its power to conduct magnetism when heated to a certain temperature. If, therefore, a core of iron surrounded by a coil be connected to a magnet by means of thin strips of iron or nickel, a current is generated in the coil of wire when the strips are alternately heated and cooled, because the lines of force are first cut off, then allowed to pass, and so on.

* *Electrical World*, Aug. 27, 1887.

This machine has the same disadvantages as the thermo-electric battery, being low in efficiency, and requiring a large apparatus for a comparatively small output.

It should be observed that neither thermo-electric nor thermo-magnetic generators are true cases of the "direct conversion" of fuel energy into electricity. In both of them the energy is first converted into heat, which introduces a certain indirectness, and, what is more objectionable, brings the apparatus under the second law of thermo-dynamics, and thereby tends to make the efficiency very low, which is characteristic of all apparatus for converting heat-energy into any other form of energy.

Primary Batteries.—Numerous attempts have been made to accomplish the strictly direct conversion of fuel-energy into electricity, but none of them can be said to be at all practicable. Jablochkoff, in 1877, patented a voltaic battery in which carbon was used as the positive plate, the exciting-fluid being fused potassium nitrate. This battery is similar in principle to an ordinary Daniell battery, but the electric current is actually produced directly from the chemical energy of fuel, and the theoretical efficiency might be nearly 100 per cent; but, unfortunately, the active fluid, or depolarizer, in this battery is very expensive. Attempts have therefore been made by other inventors and experimenters to use some fused compound which could be reoxidized by passing air through it. For example, fused sodium manganate will act in that way, but it has practical difficulties.

One of the most serious of these troubles is the fact that the *E.M.F.* would be very low, only about one volt, and the internal resistance could not be made low enough to give a large output of current with this low *E.M.F.* It necessitates, therefore, a large apparatus to generate even one horse-power. The low voltage would require a large number of cells to be used for most practical purposes, or else transformation by means of a dynamotor. There would be a tendency to an accumulation of impurities in the cell, brought there by the fuel, which would necessitate the renewal of the fused compound, and involve considerable expense. Other forms of voltaic battery might be employed for direct conversion, such, for example, as a gas-

battery consisting of two electrodes, one of which is supplied with hydrogen or carbonic oxide produced by gasifying the fuel, and the other is fed with the oxygen of the air. Batteries of this sort have been tried; but it is difficult to supply the gases at the surfaces of the plates under the liquid, where it is necessary that the action should take place.

The ordinary primary battery is almost a case of direct conversion. Commercial zinc is produced by the chemical action of fuel (carbon) upon oxide of zinc. This zinc is used in a cell where it combines, usually with sulphuric acid to form sulphate of zinc. The energy of the combination is given out in the form of electric current. The author has elsewhere discussed primary batteries in detail, and given various data of *E.M.F.*, cost, etc., of different combinations.* These figures are not encouraging, even theoretically; and it is of course a well-known fact that this source of current is not at all satisfactory when any considerable amount of current is required.

The principal objections to primary batteries are high cost, large space occupied, and great trouble in maintenance. In the paper cited, it is shown that in the cheapest cell, the Bunsen, the cost of the theoretical amount of material required would be 20 cents per horse-power hour, to which must be added a considerable amount for waste material, and for labor in taking care of the battery, making a total cost of at least 30 cents per horse-power hour. This is about 30 times as great as the cost of electric power generated by means of the engine and dynamo, and makes this source of energy entirely out of the question where anything more than a small fraction of a horse-power is needed. The zinc alone in a primary battery costs about 10 cents per horse-power hour; hence it would not help matters much if some depolarizer were discovered which would cost nothing. This shows the absurdity of the commonly advertised claims of a cheap depolarizer, with which a primary battery can supply "a large number of electric lights at a merely nominal cost."

The other common claim of a battery in which very little zinc is consumed is equally preposterous, since it is a well-

* "Possibilities and Limitations of Chemical Generators of Electricity," *Trans., Am. Inst. Elec. Eng.*, May, 1888. *The Electrical Engineer*, June, 1888.

known fact that at least 1.22 grams of zinc must be consumed per ampere hour. Hence we can calculate that if the *E.M.F.* were two volts, it would require almost exactly one pound of zinc per horse-power hour. This voltage is about as high as can be obtained in primary batteries; but even if twice this voltage could be obtained, which is practically impossible, it would still require ½ lb. of zinc per horse-power hour. The advantage of all these voltaic or chemical generators of electricity is that they are not limited by the second law of thermodynamics. They can therefore have a theoretical efficiency of nearly 100 per cent, and sometimes actually have a practical efficiency of over 90 per cent. In this respect they are much more hopeful than the apparatus in which heat-energy is converted into mechanical or electrical energy, but practically they are far inferior at present.

The conclusion drawn from the foregoing study of the possibilities of generating electricity very directly and cheaply is not particularly encouraging, and it would seem that there is no great hope of a radical improvement in this direction in the near future. Apparently it will be necessary to content ourselves with the gradual but steady improvement of the means which we already have. It is possible, however, that some entirely new principle may be discovered by which electricity can be produced; but it cannot be said that there is any immediate prospect or indication of such a discovery, although there may be hundreds of investigators working directly or indirectly upon this fascinating problem in well-equipped laboratories, both collegiate and commercial.

On the other hand there are excellent reasons for expecting great improvements in the lamp or light-giving device itself. For example, we have the interesting fact that the glowworm produces light with an efficiency far higher than that of any artificial method. Professor Langley has shown that an ordinary gas-burner emits 400 times as much heat as a glowworm when they both give exactly the same amount of light. In other words, nearly all of the energy given out by a gas-burner is invisible heat, which contributes nothing to the lighting effect; whereas, in the case of the glowworm, a large portion of the energy

emitted is in the luminous part of the spectrum. The incandescent lamp is ten times better in this respect than the gas-burner, but still only one-fortieth as efficient as the glowworm. Hence there is an enormous margin for bettering the economy of artificial methods of illumination.

The early commercial incandescent lamps made by Edison consumed more than 5 watts per candle power, whereas the present standard lamps require only 3.1 watts per candle. On the other hand the average efficiency of arc-lamps has actually diminished during the same period, because the open, direct-current arc is more efficient than the inclosed and alternating-current types by which it has to a large extent been replaced. The explanation of this anomalous change is to be found in the fact that the inclosed form saves trouble in renewal of carbons and the alternating-current lamps permit the operation of a large number from one generator, as stated on page 51.

There are, however, new kinds of lamp that show higher efficiency than the ordinary incandescent or even arc types. The Nernst lamp is about twice, and the Hewitt lamp about ten times as efficient as the carbon-filament incandescent form. These gains of 100 and 900 per cent respectively are far greater than the small and slow advances made in the economy of steam-engines and surpass even the possibilities of improvement in gas-engines, the promising features of which were given on page 78.

CHAPTER VIII.

THE STEAM-ENGINE, HISTORY AND GENERAL PRINCIPLES.

Introduction. — A general study and comparison of the various methods of generating electricity have already been given in the last chapter, including the principles of the conversion of heat into mechanical energy by means of steam and other heat engines. In taking up the special consideration of the steam-engine, it will be interesting and profitable to review briefly the history of the machine which has been such an important factor in modern civilization, because of its general applications, and because it is one of the principal sources of power employed to generate electricity.

Historical Notes. — The starting-point in the history of the steam-engine is always stated to be the simple rotary engine devised by Hero of Alexandria about two thousand years ago. This engine, a steam-fountain, and his many other steam-apparatus, were only toys, however, and were never applied to any useful purpose. The next great step was made by the Marquis of Worcester, who built a steam-engine which was an actual working machine of considerable size and power. The exact date when this machine was made is not known, but it was probably about 1628.* He published a very obscure description of it in the *Century of Inventions* in 1663. The facts in regard to this remarkable machine are shrouded in considerable doubt and mystery, probably because of the actual danger of persecution to which any one exposed himself in those early days by bringing out any invention, particularly such a radical one as the steam-engine. It appears that the engine contained the important improvement of a separate boiler, and, in fact, possessed many features that showed the remarkable genius of its inventor.

Thomas Savery, in 1698, obtained a patent for a water-raising apparatus, which was the first real attempt to use a steam-engine *commercially*. This engine acted merely by the pressure of steam

* Thurston, *Growth of the Steam Engine.*

upon the surface of the water in two chambers acting alternately, and did not contain any piston or cylinder. Denis Papin had previous to this time (1690) described a cylinder and piston engine, and had even suggested the utilization of the condensing-power of steam; but the form described had the radical defect of using one and the same vessel for boiler, cylinder, and condenser. He afterwards (1705) went back to some of Savery's ideas. Newcomen, in 1705, was the first to use a cylinder and piston and a separate boiler; but the engine still had the defect of having the condensation of the steam performed in the cylinder. It was far more practicable, however, than anything which had preceded it, and began to be used regularly for pumping water out of mines as early as 1711. These Newcomen engines required the steam to be let into and out of the cylinder through valves which had to be worked by hand. In 1713 Humphrey Potter, an ingenious boy employed to operate the valves of one of these engines, connected the valves to a moving part of the engine by cords in such a way as to cause them to work automatically, in order to save himself the trouble of attending to them. This very important invention was improved by Henry Beighton in 1718.

These improved Newcomen engines were used regularly for pumping mines until Watt made a series of brilliant inventions, which were so important and radical that he is ordinarily said to be the inventor of the steam-engine. The most valuable improvement due to Watt is the use of a condenser separate from the cylinder of the engine, which is, indeed, absolutely essential in order to avoid the enormous waste which would result from condensing the steam in the cylinder itself. This invention was made in 1765, and patented in 1769. Watt, in 1782, also patented the double-action principle, or use of steam on both sides of the piston; also the use of steam *expansively,*—that is, the introduction of a certain amount of steam into the cylinder, which does work upon the piston by expanding after the connection with the boiler has been shut off. Both of these inventions were made several years before they were patented. Besides these fundamental principles contributed by Watt, he also greatly perfected the general design and details of the mechanical construction. In fact, his work was so complete that the simple condensing engine of to-day is practically identical with the engine of Watt.

The greatest improvements in the steam-engine since the inventions of Watt are the compound or multiple-expansion engine patented by Hornblower in 1781, and revived by Woolf in 1804, also conceived by Watt; the automatic cut-off governor brought out by Corliss in 1849; and the recent development of various forms of steam-turbine.

The history of the *theory* of the steam-engine, and the science of thermo-dynamics upon which it is based, may be considered to have started when Carnot, in 1824, first showed how to treat the *cyclic* action of any heat-engine by considering each cycle separately. The use of this method in the study of heat, as well as in electricity, magnetism, and other sciences, is of the greatest value, and seems to be the best possible way to secure definiteness and completeness in scientific analysis. The determination of the mechanical equivalent of heat by Joule in 1843 (which is the most essential element in the establishment of the principle of conservation of energy) gave the real foundation to the science of heat, and, in fact, of all modern science. From 1849 onward, the science of thermo-dynamics was rapidly developed by Clausius, Rankine, and Sir William Thomson (Lord Kelvin). The publication of Rankine's classical work on the steam-engine, in 1859, gave the almost complete application of pure thermo-dynamics to the practical case of the steam-engine, and established that intimate relation between theory and practice so essential to the proper and rapid advancement of both.

The recent history of the steam-engine is made up of the development of the compound and triple-expansion types, improvements in the mechanism for governing speed, the perfection of the design and construction of the various parts, and the devising of suitable forms of engine for special work. The introduction of the steam-turbine is the latest important feature in steam-engineering. All of these modern improvements are of particular importance in connection with electric lighting; in fact, they are largely the result of progress in electric light and power.

THE PRINCIPLES OF THE STEAM-ENGINE.

A complete study of the steam-engine requires a thorough knowledge of the science of heat, and its relation to mechanics, —thermo-dynamics,—and would occupy far more space than can

be devoted to it in this treatise; but certain fundamental principles are sufficient to enable one to understand the steam-engine well enough for those who are not specialists in the subject.

The two laws upon which the entire science of heat is based, called the first and second laws of thermo-dynamics, are:—

1. *The law of the equivalence of heat and mechanical energy*, which may be stated as follows: *A given quantity of mechanical energy is always equivalent to, and can be converted into, a certain definite quantity of heat;* or, to take a concrete case, 1 heat-unit, that is, the heat required to raise 1 gram of water 1° C., is exactly equal to the mechanical work required to raise 1 gram 428 meters high; or, in the English system, 1 lb. of water heated 1° F., is equivalent to 772 foot-lbs. according to Joule, or 780 according to the latest results (page 21).

2. *The second law of thermo-dynamics* is differently stated by different authorities, and none of them are very easily understood, the statement of Rankine in particular being quite abstruse. The corollary of this law, which has practically the same significance, and is in much better form to be understood and used in connection with heat-engines, is that given on page 76, and expressed by the formula: Efficiency $= \frac{T_1 - T_2}{T_1}$. The meaning of this expression is that *the highest possible efficiency of any heat-engine is equal to the difference in temperatures between which it works divided by the initial absolute temperature.*

In any heat-engine there is the working substance, the changes in temperature of which give the action of the engine. In practice this substance is either water-vapor (steam), gas, or air, and is called the fluid. There are two important laws giving the relations between the temperature, pressure, and volume of a gas:—

1. The law of Boyle or Mariotte, which states that the volume of a gas is inversely proportional to the pressure, the temperature being kept constant; that is, $p v = C$, in which p and v are the pressure and volume respectively, and C is a constant depending upon the density and other properties of the gas.

2. The law of Charles or Gay Lussac, which states that a gas increases $\frac{1}{273}$ of its volume at 0° C. for each degree of rise in temperature; that is, $v_t = v_0 \left(1 + \frac{t}{273}\right)$, in which v_t is the

volume at any given temperature, t in centigrade degrees, and v_0 is the volume at zero. The combined expression for these two laws is $pv = R(t + 273)$. Now, since $t + 273$ is the absolute temperature, T, we have $pv = RT$.

The above laws apply, however, only to a perfect gas, such as air, or any other permanent gas; hence they can be used in discussing gas and hot-air engines, but they have to be considerably modified in order to apply them to the case of steam or other vapor, the action of which is quite different from that of a perfect gas. The properties of steam, and the relations between its pressure, volume, and temperature, are usually given in the form of a table similar to the one printed below. The figures are for steam, which is neither superheated nor supersaturated (i.e., "wet"). The data for either of these latter kinds of steam are somewhat different, depending upon the degree of superheating or supersaturation.

Table of the Properties of Saturated Steam.

Absolute Pressure. Lbs. per Sq. In. above Vacuum.	Temperature, Fahrenheit.	Total Heat of Evap. from 32°.	Density. (Weight of Cu. Ft. in Lbs.)	Volume of 1 Lb. in Cu. Ft.
1	102	1113.1	.00303	330.4
5	162.4	1131.5	.01378	72.56
10	193.3	1140.9	.02644	37.83
14.7	212	1146.6	.03793	26.37
20	228	1151.5	.0507	19.73
30	250.3	1158.3	.0742	13.48
40	267.2	1163.4	.09723	10.28
50	280.9	1167.6	.11993	8.34
60	292.6	1171.2	.14236	7.024
70	302.8	1174.3	.16458	6.076
80	311.9	1177.1	.18663	5.358
90	320.1	1179.6	.20853	4.796
100	327.6	1181.9	.2303	4.342
110	334.6	1184	.2519	3.97
120	341.1	1186	.2735	3.66
130	347.1	1187.8	.295	3.39
140	352.8	1189.6	.3163	3.16
150	358.2	1191.2	.338	2.96
175	370.5	1195	.390	2.56
200	381.6	1198.3	.443	2.26
250	400.9	1204.2	.548	1.83
300	417.4	1209.2	.652	1.54
400	445	1217.7	.857	1.17
500	467.4	1224.5	1.062	.94

This is taken from Thurston's *Manual of the Steam Engine*, Part I., page 820, which contains complete tables of the data of steam. The pressure above that of the atmosphere, as shown

by an ordinary gauge, is 14.7 lbs. less than the figure in the first column.

The action in a steam-, gas- or other heat-engine can be determined analytically by applying the principles stated above. It is necessary, however, to take account of various practical conditions. For example: the steam or gas loses heat to the walls of the cylinder; the valves cause a certain loss of pressure, or introduce back-pressure, and the action of steam depends much upon whether it is "wet," saturated or superheated. The result is that such problems are difficult to solve and require a thorough knowledge of the science of thermo-dynamics and the technology of engines. The student is therefore referred to the special works on these subjects given in the bibliographies of the steam-engine and gas-engine on pages 194 and 209 respectively.

The practical method is to determine directly, by means of an indicator, the curve (Fig. 26) representing the actual variations of the pressure in the cylinder throughout a complete cycle (forward and back stroke). The area of this indicator diagram found by a planimeter, gives the work done by the steam or gas on the piston during that cycle, whatever the law of expansion.

CHAPTER IX.

STEAM-BOILERS FOR ELECTRIC LIGHTING.

A STEAM-BOILER is a vessel in which water is evaporated by heat produced by the combustion of fuel, the resulting steam being used in a steam-engine for the generation of mechanical power. Boilers are made of wrought-iron or mild steel, and with careful limitations, cast iron is used for certain parts. The form and construction of boilers depend upon the purpose for which they are to be used, the character of fuel employed, and other circumstances. The kinds of fuel available for steam-boilers, and the data concerning each, are given in the following table:—

FUEL.	SPECIFIC GRAVITY. Average.	AIR REQUIRED per Lb. of Fuel. Twice the Theoretical.	TEMPERATURE OF COMBUSTION with Twice the Theoretical Supply of Air.	HEATING-POWER PER POUND.		
				In Heat-Units Lb.-Cent.	Theoretical Amount of Water evap. at 100° C.	Practical Amount of Water evap. in boiler.
Petroleum —						
Crude . .	.88	31 lbs.	1500° C.	11500	21.3	14 to 16 lbs.
Coal —						
Anthracite .	1.45	24	1400	7500	14	8 to 10 lbs.
Bituminous.	1.3	25	1425	8000	14.8	8 to 10 lbs.
Coke . . .	.75	24	1400	7500	14	8 to 10 lbs.
Wood (Hard)—						
Kiln dried .	.5 to .9	12	1200	3800	7	4 to 5 lbs.
Air dried .	.6 to 1	9.8	1100	2900	5.4	3 to 4 lbs.

In calculating the weight or volume of air required for combustion, the following data are useful:—

One pound of air at ordinary barometric pressure, and at 15° C. (59° F.), is almost exactly 13 cubic feet, and contains .23 lb. of oxygen. The volume, V_t, at any other temperature, by Gay Lussac's law (page 89), is, $V_t = \frac{273+t}{273+15} \times 13 = \frac{13}{288}(273+t)$, in which t is the temperature centigrade. The volume, V_p, at any given pressure is, $V_p = \frac{14.7}{P} V_t$, in which P is the pressure in pounds per square inch above vacuum, and V_t is the volume at the given temperature, as found by the preceding formula.

The heat of combustion of a fuel may be calculated approximately by the formula:* —

Heat in centigrade units = $8140\,C + 34500\,H - 3000(O+N)$.

Heat in Fahrenheit units = $14650\,C + 62100\,H - 5400(O+N)$.

In these equations the letters C, H, O, and N represent the weights of carbon, hydrogen, oxygen, and nitrogen (exclusive of ash and moisture) in the fuel.

The air required for combustion may be calculated approximately by the formula, weight of air $= 11.5\,C + 34\,(H - \frac{1}{8}\,O)$, in which C, H, and O are the weights of carbon, hydrogen, and oxygen respectively. This weight of air is the theoretical amount, however, and should be increased from fifty to one hundred per cent to obtain complete combustion.

The use of a poor quality of coal on account of cheapness is usually bad economy, as the percentage of ash is much larger, so that the cost of the combustible part of the fuel may be as great in cheap as in more expensive coal. Another disadvantage of cheap coal is the fact that a given boiler will not produce so much steam with it, consequently it takes a larger boiler, or a greater number, to produce the same amount of steam, which would add to the first cost as well as to the interest and depreciation on the plant. The trouble and expense of firing the boilers, handling ashes, etc., are also greater with poor coal.

Bituminous coal is more generally employed for steam generation throughout the world than anthracite; but in certain localities the latter is used exclusively, as, for example, in New York City, where the burning of the former is practically prohibited by the Board of Health. The engineer should always study carefully the local conditions of coal supply.

Wood as a fuel for boilers is quite common in localities where it is very cheap, being sometimes much cheaper than coal; as, for example, in Maine, Oregon, Washington, and other States where large forests still exist. The various kinds of wood, when dry, have practically the same evaporative value *per pound*. This is usually estimated at .4 the value of the same weight of coal. Wood is a fairly good fuel for boilers, where it is available and sufficiently cheap. Sawdust can be utilized as fuel for boilers, but a special furnace and automatic feeding-devices are

* "Notes on Steam Boilers," by Peabody & Miller, Boston, 1894.

required. Even spent tan-bark is sometimes employed, usually mixed with coal. Bagasse, the refuse of sugar-cane, is largely used as fuel in Cuba.

Petroleum, which is practically the only natural liquid fuel, has been largely used for boilers, and in many respects it has great advantages. The dust, dirt, smoke, ashes, and labor incidental to the use of coal are almost entirely avoided by employing petroleum. Some special form of burner is required, in which the oil is reduced to a fine spray by means of a steam or air jet. Great claims have been made concerning the economy of petroleum as fuel, but it is a question whether the actual results entirely justify the claims.* The chief practical difficulty in the use of petroleum is the fact that the heat is not widely or uniformly distributed, being very intense at certain points where it is liable to injure the boiler. The heat-units produced by petroleum when completely burned are about 50 per cent greater than from the same weight of coal; but, owing to the fact that it can be burned more perfectly, it has been found by experiments in this country, and also in Russia, that 1 lb. of petroleum is equal to 1.8 to 2 lbs. of coal. A gallon (U. S.) of petroleum weighs about 6.5 lbs., and is therefore equivalent under a boiler to about 11 to 13 lbs. of coal; and about 180 gallons are equal to a gross ton (2,240 lbs.) of coal, or about 160 gallons to one ton of 2,000 lbs. At the oil-wells, petroleum is worth about 2 to 3 cents per gallon, or .84 to $1.26 per barrel of 42 gallons, which is equivalent to $3.60 to $5.40 per ton for coal. The lowest price at which oil can be delivered in the vicinity of New York is about 3 to 4 cents per gallon, making it cost the same as coal at $5.40 to $7.20 per ton, which is more than the ordinary price of coal in the City of New York. Hence it would not seem to be cheaper than coal, even allowing for its more perfect combustion. The steam used to convert the oil into spray, or "dust," consumes considerable power, which is often forgotten in determining the cost of petroleum as fuel. Petroleum was employed exclusively, on account of its convenience and cleanliness, as fuel in the enormous plant of boilers at the Chicago Exposition of 1893.† The boilers there

* "Committee Report to American Street Railway Association, October, 1893," by E. G. Connette, chairman. *Electrical Engineer* (N.Y.), Oct. 25, 1893, p. 365.

† *Scientific American*, July 8, 1893.

heated by oil aggregated 20,500 horse-power, and it is stated that 1 lb. of oil evaporated 15 lbs. of water in that case.

Natural gas as a fuel possesses the advantages of cleanliness and convenience to an even greater extent than oil. In fact, it is almost ideal in these respects, and has been used extensively in districts where it is available. The disadvantages are uncertainty as to the continuance of the supply, intense localization of heat, similar to that produced by oil, and danger of explosion. In some cases the supply of gas has actually ceased; and it is a fact that quite a number of explosions have occurred, with serious results, due to the use of natural gas. The heating-power of natural gas is usually about 2 to 2.5 times that of the same weight of coal, or about 30,000 cubic feet are equivalent to a ton of coal.

Solid or liquid fuel can be converted into gas by means of a gas-producer (p. 200). In some forms of producer the carbon of the coal is converted into carbon monoxide by partial combustion ($2C + O_2 + 4N_2 = 2CO + 4N_2$); the resulting gas is conveyed to the boiler, where it is completely burned to carbon dioxide ($2CO + 4N_2 + O_2 + 4N_2 = 2CO_2 + 8N_2$). This method has the disadvantage of losing a considerable fraction of the heat in the first operation, and the resulting gas is much diluted with nitrogen. Another process of gasifying fuel is to convert it into water-gas, by treating it at a high temperature with steam, which is decomposed, hydrogen and carbon monoxide being formed, both of which are highly combustible ($C+H_2O=CO+H_2$). Petroleum may be gasified by passing it through very hot pipes, thus "cracking" it up into gaseous compounds, or by treating it with steam at a high temperature, thereby forming water-gas. But, as stated above, it is commonly used in the form of a spray, or "dust," obtained by the action of a steam- or air-jet.

Natural gas or the gas produced from solid or liquid fuel can be used in burners under boilers to produce steam. The advantages are the cleanliness and convenience resulting from the elimination of coal, ashes and smoke. The starting up of the fire and the regulation of the heat are also greatly facilitated, but there are the disadvantages already stated. This matter is considered further in connection with gas-engines.

Artificial fuel is sometimes used, consisting of various mixtures of coal-dust, or slack and other materials, with tar, pitch, or

equivalent material, to hold the particles together. It is usually pressed and baked in the form of blocks. These are commonly called "patent fuels." Their heating-power is about equal to that of the same weight of coal, but they are apt to have more ash. It is sometimes kept as a reserve supply in stations, where the square form enables it to be conveniently and compactly piled away in any available space.

Construction of Boilers. — The materials chiefly used in the construction of boilers are wrought iron or mild steel. The tensile strength of the former ranges from 40,000 to 60,000 lbs. per square inch. Professor Unwin * gives the average tenacity of iron plates as 46,000 lbs. per square inch, and steel plates 62,000

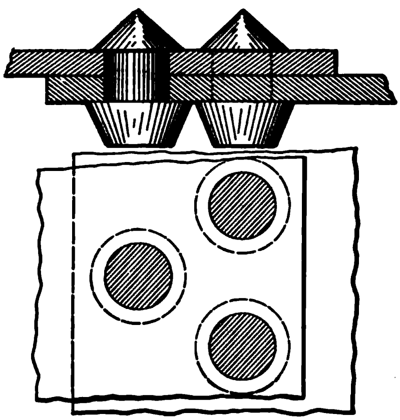


Fig. 11. Double-riveted Lap-Joint.

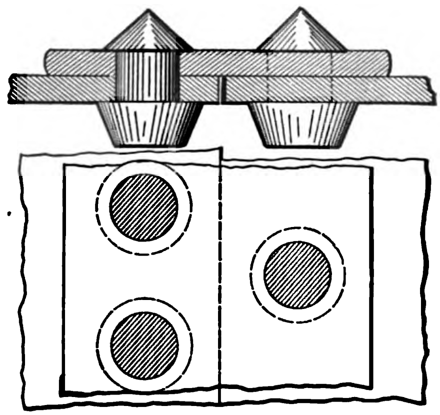


Fig. 12. Single-riveted Butt-Joint.

lbs. Cast iron is also used for certain parts of some types of boilers, but it is liable to crack, and its tensile strength is not nearly as much as that of wrought iron, being only about 15,000 to 25,000 lbs. per square inch; and even these figures cannot be relied upon, the modern practice being to eliminate cast iron entirely in parts of the boiler proper.

Boiler-shells are built up of sheets of wrought iron or wrought steel riveted together. Rivet-joints may either be lap-joints, as shown in Fig. 11, or butt-joints, Fig. 12, either of which may be single riveted or double riveted; and in high-pressure boilers the butt-joint has straps on both sides. The strength of riveted

* *Elements of Machine Design*, 1891, p. 112.

joints determines more than any other factor the safety of boilers, and they depend upon the following facts:—

1. The strength of the plate to resist being torn along the center line of a row of rivet-holes.

2. The resistance of the rivets against shearing.

3. The strength of the rivet or of the plate around the rivet to withstand crushing.

4. The resistance of the plate against being torn between the rivet-holes and the edge of the plate.

5. Friction between the plates, due to the force with which they are held together by the rivet. This last, however, should not be relied upon.

Before taking up the detailed study of the various forms of boiler, it will be well to consider the requirements of a perfect steam-boiler, which are many and difficult to obtain. These are as follows: The best material obtainable, and the highest grade of mechanical design and workmanship; freedom from danger of explosion; economy in the use of fuel, and cost of maintenance; considerable storage capacity for steam and water; constant and free circulation of water; a large surface for the disengagement of steam in order to avoid "priming," i.e., foaming; all parts readily accessible for cleaning and repairs; complete combustion of the fuel should take place before the gases escape to the chimney; joints and other weak parts should be removed as much as possible from the direct action of the fire; heating-surfaces should be of sufficient extent, and formed or arranged so as to extract as much of the heat as possible from the gases; the repairs required should be a minimum, since these cause great trouble and expense.

In addition to the above general requirements of steam-boilers, there are certain special requirements for each particular use to which they may be applied. In electric lighting, the special quality which a boiler should possess is ability to maintain a constant pressure; and it is particularly important that the pressure should not fall at full load. This quality is obviously desirable in almost any case; but it is of peculiar and vital importance in electric lighting, because the slightest variation in speed is objectionable, a change of even a small fraction of one per cent in voltage producing a perceptible fluctuation

in the light of an incandescent lamp. It might be said that the engine ought to govern for variations in steam-pressure; that is, maintain a constant speed irrespective of small changes in pressure. To a great extent such is the case; but when there are a large number of lamps in use, the load on the engine and dynamo and the loss of potential on the conductors being at a maximum, a decrease in steam-pressure would certainly tend to aggravate the difficulty. In stating that a boiler for electric lighting should give a constant pressure, it is not intended to imply that a boiler is necessarily always run at any particular pressure. It is a common practice to use lower steam-pressures for light loads and higher pressures for heavy loads; but in any case the boiler should *maintain* the given pressure. Another special requirement which a boiler for electric lighting should fulfill, is the ability to take care of wide variations in the load, which often occur in electric lighting. These are rarely rapid, however, being mostly due to the gradual increase or decrease of daylight; but the approach of a thunder-storm may cause a sudden and large increase in load. Two radically different methods may be adopted to provide for fluctuations in load which occur in electric lighting.

The first of these consists simply in employing boilers of the so-called "quick-steaming" type; that is, boilers with large heating-surface and comparatively small water capacity, which can be quickly brought into condition for use. This plan is largely followed, and water-tube boilers which are particularly quick-steaming are in use in most of the important central stations of the large cities of both Europe and America. The other method, which is almost diametrically opposite to the first, is that of "thermal storage," proposed by Mr. Druitt Halpin, and advocated by Professor W. C. Unwin * and Professor George Forbes.† The scheme consists in using boilers having only a capacity sufficient for the *average* load, these being run continuously day and night. At times of light load the steam is carried through pipes to large iron reservoirs of cheap construction, in which it heats a large quantity of water to a

* *Lecture before the Society of Arts*, London, January, 1893.

† Paper on "Thermal Storage for Central Stations," before Nat. Elec. Light Assoc., March 1, 1893. *Elec. World*, March 11, 1893.

high temperature. When heavy demand for light arises in the evening, steam is drawn from these reservoirs. Loss of heat by radiation from the reservoirs can be made small by covering them with non-conducting material. Mr. Halpin claims to replace 22 boilers, working in the ordinary way, by 5 boilers and 92 storage cylinders, which are cheap to construct and have less depreciation than the boilers. The advantage of this system would be that wear and the waste of fuel involved in firing up boilers for a few hours' work is avoided. Practically the same result is obtained with ordinary boilers by banking the fires of some of them during light load. The consumption of fuel is then small, the maximum capacity is large, and the presence of two different kinds of apparatus is avoided. Another plan open to the last-named objection but sometimes recommended employs horizontal (fire) tubular boilers to carry the ordinary load, the water-tube type being also installed to take care of the variable portion of the load. In this way a large part of the steam is supplied by cheap boilers, and the more expensive type is needed only to meet the extra demands.

The various kinds of boilers may be classified as follows:—

STEAM-BOILERS.

CLASSES.	TYPES.
1. Plain cylinder boilers.	"Egg-ended" type.
2. Flue boilers.	Cornish type, single flue. Lancashire type, two flues. Galloway type, "breeches" flue.
3. Multitubular or "fire-tube" boilers.	Return tubular boiler. Locomotive boiler. Marine boiler.
4. Water-tube or "sectional" boilers.	Babcock and Wilcox and many other types.
5. Coil boilers.	Torpedo-boat and other types.
6. Vertical boilers.	Various types which are usually modified forms of horizontal boilers.

Many of these types are not used to any extent in electric lighting, and need not be considered. The forms of boiler commonly employed are: The water-tube boiler, the ordinary return tubular boiler, the locomotive type of boiler, and the vertical boiler.

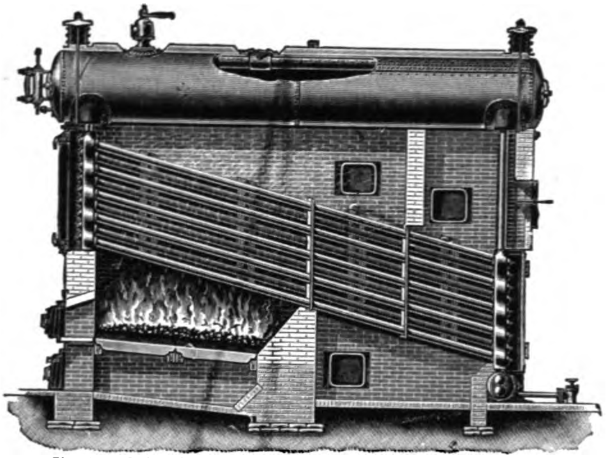


Fig. 13. Babcock & Wilcox's Sectional or Water-tube Boiler.

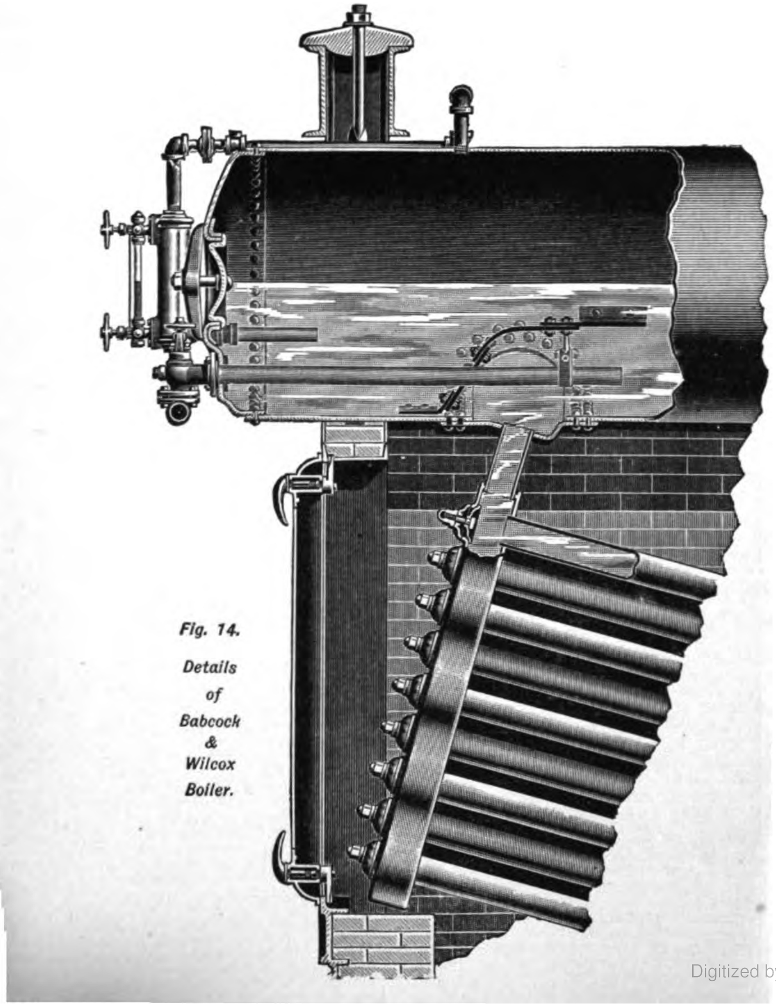


Fig. 14. Details of Babcock & Wilcox Boiler.

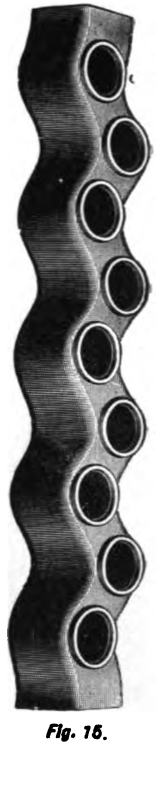


Fig. 15.

As already stated, water-tube boilers of the Babcock & Wilcox and other types are very extensively used in electric lighting. They possess the advantages of being quick-steaming, not liable to disastrous explosions, easy to repair and transport in sections, the parts can be carried through ordinary doors or windows, and water-tube boilers being light can be put on the second or third floor (p. 47). This type is open to the objections that they are rather expensive, have not much capacity for water or steam and cannot, therefore, stand a large and sudden increase of load, which, however, is not likely to occur in electric lighting. On the other hand they can supply a large demand if gradually made.

The Babcock & Wilcox water-tube boiler, shown in Figs. 13, 14, and 15, is very generally used for electric lighting and other purposes in this country and many foreign countries. This and other similar types of boiler consist of a large number of parallel iron tubes joined at their ends by "headers," or connecting pieces of steel or cast iron. The former construction is preferable, being necessary in high-pressure boilers. These tubes are ordinarily four inches in diameter, and are placed at a distance apart about equal to their diameter. The tubes are "staggered," or arranged so that each tube is immediately over the space between two tubes in the row below. The object of this arrangement is thoroughly to abstract the heat from the products of combustion. The mass of tubes are connected at both ends to the long horizontal steam and water drum above, the water-level being kept at such a height that this drum is about half full, as shown. At the rear the tubes are connected to the mud-drum below, into which the dirt, scale, etc., settles. The latest form of these boilers has vertical headers both front and back, as represented in Fig. 13. A similar arrangement was adopted in the earliest forms of Babcock & Wilcox boiler originally patented in 1867. But for many years inclined headers were universally employed at both ends, the upper or front one being shown in Fig. 14. The construction with vertical headers was introduced about 1900, the saving in horizontal space thus secured being about 10 per cent. Caps held in place by clamps and bolts at both ends of each tube are easily removed to permit its inspection, cleaning, or renewal.

The path of the products of combustion is shown in Fig. 13.

They first pass directly upward from the grate, through all the water-tubes, being obliged to take this path by the bridge-wall at the back of the fire-box and a baffle-plate or partition which

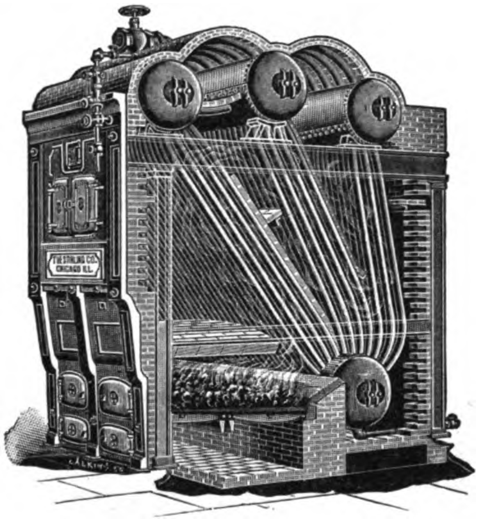


Fig. 16. Stirling Water-Tube Boiler.

surrounds the tubes, and forms an extension of the bridge-wall. About half-way between this wall and the rear end of the tubes is another baffle-plate, above which is a hanging wall of brick. These, together, cause the gases to pass downward through the tubes, and finally upward again at the back, thus flowing three times through the entire mass of tubes.

The circulation of the water is also very effective in these types of boiler. The inclined position of the tubes causes the heated water to flow from the rear toward the front of the boiler, thus traveling in a direction opposite to that of the gases. In this way the water is acted upon by hotter gases the higher its own temperature becomes.

There are many other well-known types of water-tube boilers which are similar in principle but differ considerably in details of construction. Among these may be mentioned the Root, National, Heine, and Stirling.

In Europe the Steinmuller and other forms of water-tube boiler are used in addition to the Babcock & Wilcox, which latter is as widely used there as in America. All these types of

water-tube boilers are employed in electric lighting; in fact, it is one of their most important applications.

Cylindrical or Horizontal-Tubular Boilers. — A typical form is shown in Fig. 17, and consists of a cylindrical *shell*, closed at the ends by two flat *tube-plates*, through which the *fire-tubes* extend from one end to the other. The diameter of the fire-tubes is usually about 3 or 4 inches. Nearly two-thirds of the volume of the boiler is filled with water, the remaining space being reserved for the steam. The water-level is 6 to 8 inches above the top row of tubes. The tubes act as *stays* for the tube-plates below the water-line; but above the water-level the flat plates must be stayed by *through rods* from one plate to the other, or by diagonal stays to the shell of the boiler.

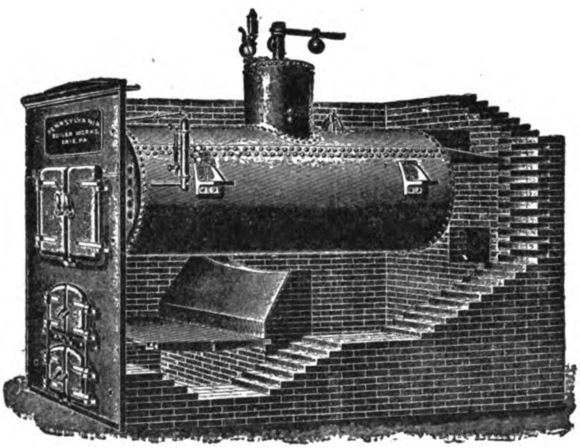


Fig. 17. Horizontal-Tubular Boiler.

The grate is under the *front end* of the boiler, and the products of combustion pass back under the boiler. A *bridge-wall* at the rear end of the grate is arranged to throw the gases into contact with the boiler. The gases return through the tubes, and pass out by the *up-take*, or flue leading to the chimney. The boiler is supported by cast-iron brackets, which are riveted to the shell, and rest on the side walls. A vertical *steam-dome* projects from the top of the boiler from which the steam is drawn. These boilers are made in sizes from about 3 feet in diameter and 7 feet long, having 12 horse-power capacity, to 7 feet in diameter and 20 feet long, having 200 horse-power capacity.

This assumes about 15 square feet of heating-surface per horse-power which is a safe rating for this type of boiler.

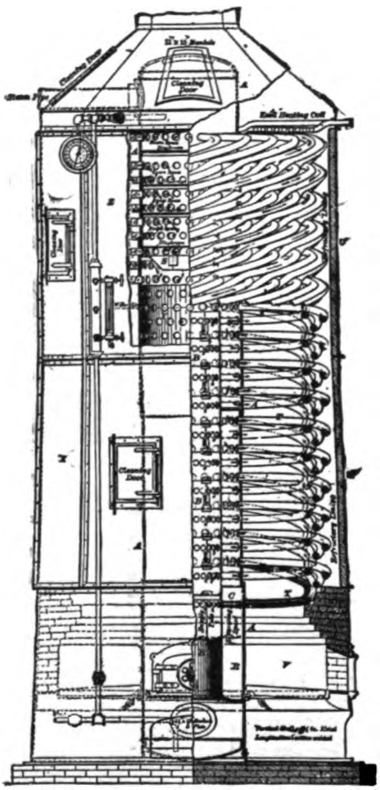


Fig. 18 a. "Climax" Vertical Boiler.

The Locomotive Boiler differs from the cylindrical-tubular in the fact that a rectangular *fire-box* is formed on the front of the boiler, and the products of combustion pass directly from the fire-box through the tubes to the end of the boiler, and out to the smoke-stack. Thus the gases make only one passage, whereas they pass forward again in the cylindrical-tubular boiler, which is therefore often called "return-tubular."

The "Climax" Vertical Steam-Boiler.—The construction of this boiler is shown in Fig. 18 *a*. The principal heating-surface is made up of the loop-like tubes *T*, which are expanded into the cylindrical shell *A*, two of them being shown blackened in the horizontal section (Fig. 18 *b*). Within the shell *A* is a second cylinder, *B*, which is not necessarily steam or water tight, and is bolted together in short sections for convenience of removal in case of repairs. The cylinder *B* is closed at the bottom and open at the top, which is a little below the water-level. The lower end of each tube *T* is connected to the inner cylinder *B* by means of a short tube *C*. These short tubes are not expanded, as it is not required that they should be tight. This arrangement is for the purpose of keeping up a rapid and constant circulation of water in the tubes *T*. The fire-box *V* surrounds the cylinder *A*, and the hot gases must pass

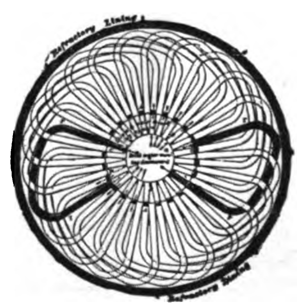


Fig. 18 b.

around all of the tubes on their way to the chimney. With a stationary grate several firing-doors are required for feeding coal on all sides; but a rotary grate is sometimes employed with this boiler, in which case only one fire-door is necessary.

Boiler-Setting. — Manufacturers of boilers usually have plans for setting which are specially adapted to each particular type; and it is well to follow these as closely as possible, in order to get the best results from a given boiler. Fig. 17 shows a setting for the ordinary horizontal tubular boiler. It consists of a cast-iron front, and brick walls 12 to 16 inches thick, which inclose and carry the boiler. Where the flame strikes, or the temperature is high, there is a lining of one layer of fire-brick, laid with fire-clay. The side walls are prevented from bulging by vertical *buck-staves*, held together by through rods. Stays or other construction of wrought iron should not be exposed to the heat, as it tends to warp badly. It should be protected by brickwork; or cast iron, which is warped less by heat, may be substituted.

The water-tube types of boiler are supported on a frame made of iron beams, which is inclosed or filled in with walls of brickwork, as shown in Figs. 13 and 16.

Grates. — The grate usually consists of fire-bars of cast iron, upon which the fuel rests. These bars are about $\frac{3}{4}$ to 1 inch thick; and the distance between them is from $\frac{1}{4}$ to $\frac{1}{2}$ inch, the rule being that for coal the open space between the grate-bars should be from $\frac{1}{4}$ to $\frac{1}{2}$ of the total grate area. For wood or for forced draught, the open space need not be more than $\frac{1}{6}$ to $\frac{1}{5}$ of the grate area. The depth of the grate-bars is about 2 inches at the ends, and 3 to 5 inches in the middle; and their length is from 2 to $3\frac{1}{2}$ feet. The grate has a maximum length of 6 or 7 feet, made up of two long or three short bars, end to end, and has a width of not more than 4 or 5 feet, in order to allow the fireman to properly feed it with coal. The grate-bars have projections at each end, and usually in the middle also, to keep them at the proper distance apart; and they are simply laid upon cross-bearers of iron, so as to be readily taken out. The thickness of the grate-bars should diminish towards the lower edge, in order to allow free entrance for the air and better escape for the ashes. Each square foot of grate surface will properly burn 15 to 18 lbs. of coal per hour with a good natural draught equal to, say, $\frac{3}{4}$ to

1½ inch of water. In the case of tubular boilers, the draught area through the tubes should not be less than one-sixth, nor more than one-quarter, of the grate surface.

By means of a forced draught, a much greater rate of consumption can be obtained; but this would not ordinarily be necessary or desirable in electric lighting. A steam-jet in the chimney, or some other means of forcing or aiding the draught, is often very convenient, however, in starting up the fire, or at times when the draught is poor.

Some form of rocking-grate, of which Fig. 19 shows an example, is usually desirable, particularly with anthracite coal. These

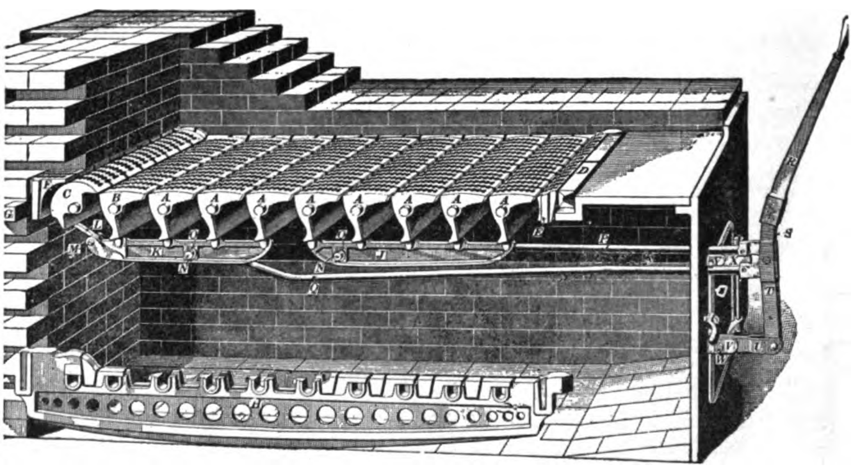


Fig. 19. McClave Rocking-Grate.

facilitate the work of the fireman. The removed portion, *H*, shown below, should rest at *G* and *D*, and carries the pins *A A*.

Boilers are sometimes "fired" by means of mechanical stokers, which are driven by a small steam-engine or electric motor, and act automatically to furnish the boiler with a continuous supply of coal. Uniformity of feed and saving of labor are secured by these devices, one form of which is shown in Fig. 20. The objection to mechanical stokers, in addition to their first cost and liability to get out of order, is the fact that they feed without regard to the demands upon the boiler, whereas a fireman can suit the supply of coal to the circumstances. Experience seems to show that the loss from this

cause with a mechanical stoker is about equal to the wages of the fireman; and there is the advantage of being rid of trouble from strikes and incompetent workmen.

The construction of the chimney was considered on page 68. The ordinary height is 75 to 200 feet. A chimney 175 feet high

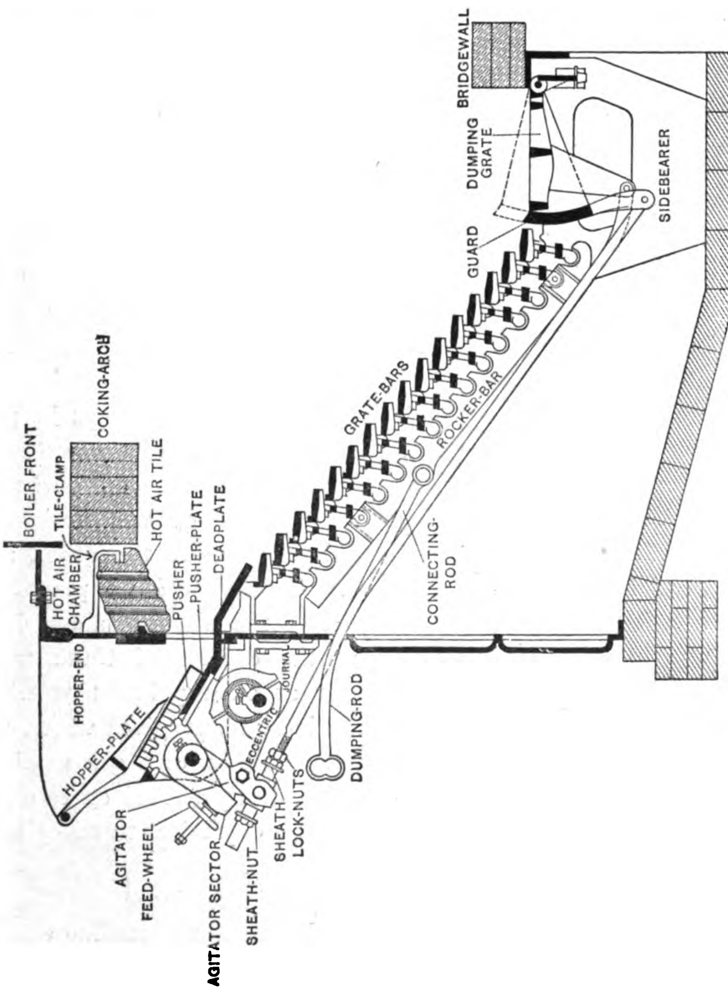


Fig. 20. Details of Construction of Roney Mechanical Stoker.

will give a draught of $1\frac{1}{4}$ inch of water, and with 8 feet internal diameter is sufficient for a 2,000 H.P. plant. The gases in the chimney should be from 200° to 250° C. Higher temperatures are not economical, since they do not greatly increase the draught and involve waste of heat. Where several boilers connect with the

same flue, they are likely to interfere with each other's draught. This may be avoided by placing a deflecting-plate where each connects with the flue, this plate being bent in the direction that the gases should go. The main damper is put in the flue near where it enters the chimney. Automatic damper regulators are often used in electric-lighting, and although they do not maintain perfectly constant pressure, their action being prompt tends to counteract great variations. They usually operate by direct action of the steam-pressure upon a piston or diaphragm, the motion of which opens or closes the damper through a mechanical connection.

Manholes. — A fire-tube boiler should be provided with one or more manholes, to allow a man to get inside to inspect, clean, or repair it. The hole is made oval in shape, partly to conform to the form of the body, and partly because a door of that shape can be passed through the hole, which is not the case with a circular door. A manhole is from 14 to 18 inches long, and from 10 to 13 inches wide.

Water-Level Indicators. — Two devices should always be provided on every boiler to show the exact height of the water in the boiler, these being the water-gauge and the test cocks or gauge. The water-gauge (Fig. 14) consists of two horizontal tubes leading into the boiler, one directly above the other, and connected by a thick glass tube. This should be placed at such a height that the normal level of the water is about half-way up the glass tube. Gauge-cocks consist of three small faucets, placed one above the other at such points that when the water is at its proper level the lowest one gives water, the top one gives steam, and the intermediate one gives mixed steam and water, when they are successively turned on to allow a little escape. These should be frequently tried, to make sure what the true water-level is; because the glass water-gauge is apt to become clogged, and give a false indication of the height of water. More accidents are due to inattention regarding water-gauges than to all other causes combined. Too low a water-level is one of the most dangerous conditions that can possibly exist in a boiler. Other means are also used to show the water-level, or to guard against its becoming too low. One of these consists of a float connected to a valve, which is opened when the water-level becomes too low, and the escape of steam causes a

whistle to blow and give warning. Fusible plugs are also placed in the boiler at such a height as to be covered by the water when it is at the proper level; but when it falls too low the plug is no longer kept cool by the water, and is fused by the heat of the fire, which allows the steam to escape and warns the fireman.

Pressure-Gauge. — Every boiler must have an accurate and reliable pressure-gauge to indicate the exact steam-pressure. In addition to the ordinary gauge, some good form of recording pressure-gauge is recommended as giving a permanent record, and acting as a check on the fireman. The instrument may be placed in the office or engine-room, at any desired distance from the boiler, the full pressure being transmitted to it by a small pipe.

Safety-Valve. — This is simply a loaded valve which is lifted, and allows the steam to escape when the pressure rises above a certain amount. The load on the valve may consist of either a weight or a spring. The pressure-gauge and the safety-valve act as a check upon each other, and the failure of one would generally be indicated by the other; but since so very much depends upon them, they should be of the best possible construction, and should be carefully examined and tested at frequent intervals.

Feed-Water Purification. — The water used in steam-boilers is obtained either from the regular city water-supply, or from some source such as a pond, river, or well. Which of these is best to employ depends upon the circumstances in each particular case; but in almost every instance the question of the purity of the water is an important matter. Almost any water available for use in boilers contains from 10 to 100 grains of solid material per gallon; and since a 100 horse-power boiler evaporates about 30,000 lbs. of water per day of 10 hours, or about 400 tons per month, the accumulation of this material becomes very considerable, being from 75 to 750 lbs. per month, assuming only half of it to be deposited. Impurities in water are of two distinct kinds: First, small particles of solid material mechanically held in suspension, the presence of which is perfectly evident to the eye, forming what is called, in plain language, muddy or dirty water. The other class of impurities are mineral substances dissolved in water, producing little or no change in its appearance or transparency.

Impurities of the first kind can be removed by filtering, or by

simply allowing the suspended particles to settle; but impurities actually dissolved in the water can only be eliminated by some process of chemical or physical precipitation. The so-called "hard water" is simply water containing compounds of lime, magnesia, etc., in solution, which are particularly objectionable in water for boilers, since they are deposited as a scale or incrustation upon the interior, and seriously interfere with the transmission of heat through the metal, thereby reducing the efficiency of the boiler, and also introducing a danger that it will become excessively heated and weakened. These deposits in boilers sometimes reach a thickness of half an inch or more, and are extremely troublesome and difficult to prevent, or to remove after they have formed. It is estimated that scale $\frac{1}{16}$ inch thick necessitates the use of about 10 per cent more fuel, $\frac{1}{4}$ inch almost 40 per cent more, and $\frac{1}{2}$ to $\frac{3}{4}$ inch scale actually doubles the amount of fuel required to generate a given quantity of steam. These facts, and the greatly increased repairs and danger arising from scale in boilers, show the great importance of eliminating it.

Feed-water purifiers of various forms are employed to rid the

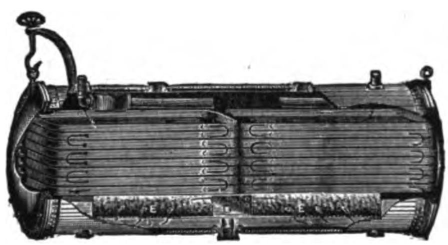


Fig. 21. Stillwell Feed-water Purifier and Heater.

water of these impurities. They usually consist of vessels or collections of tubes in which the water is heated, as represented in Fig. 21, the object being to deposit the impurities in the purifier, from which they can be easily removed, instead of in the boiler itself. Indeed, any form of feed-water heater (page 113) or economizer (page 113) also acts in the same way.

The chemical treatment of the water previous to introducing it into the boiler to remove the dissolved impurities is not particularly practicable, but in some cases it may be beneficial. For this purpose one may use some substance which, when added to the water, precipitates the foreign matter, so that it can be removed

by filtering, or by permitting it to settle. For example, carbonate of lime or magnesia is one of the most common impurities in water, but it is only soluble in water charged with carbonic acid; hence if milk of lime or caustic soda be put in the water, the carbonic acid combines with it, which causes the carbonate of lime to be precipitated. The sulphates of lime and magnesia, which next to the carbonates are the most common impurities in water, may be precipitated by adding carbonate of soda or soda-ash to the water. The precipitate, which is a white powder, may be removed from the water by filtration, or may be blown out of the boiler from time to time, and is far less objectionable than the hard adherent scale formed by the sulphates. Deposits in boilers may be removed by the simple operation of "blowing off," which consists in allowing a certain amount of water to escape from the mud-drum, thereby carrying away the dirt and precipitates which tend to collect in it. Actual cleaning with scrapers is necessary if the deposit has formed on the tubes or shell of the boiler, and has reached a thickness of $\frac{1}{8}$ or $\frac{1}{4}$ inch. There are many "boiler compounds" which are put into the boiler, and intended to dissolve, loosen, or otherwise get rid of the scale. These last remedies are somewhat similar to "quack medicines;" but they are quite popular in places where the hardness of the water gives great trouble, and is often so serious that almost any remedy is welcome. Oak, hemlock, and other barks, logwood and similar substances, are effective in water containing carbonate of lime or magnesia, by reason of their tannic acid, which produces a precipitate that is held in suspension, and does not deposit as scale; but the tannic acid is injurious to the iron, being apt to corrode it. The same objection applies to molasses, vinegar, fruits, etc., which have also been used; but their acetic acid eats away the iron.

Oil is frequently put into boilers to prevent the scale from adhering; but great care should be observed in its use, as it is likely to cause foaming and other troubles. The best oil is a high-grade kerosene; and any oil that is heavy (i.e. has "body") is very objectionable, because it tends to occasion foam, and also forms films or accumulations which prevent the water from coming in contact with the iron, thereby allowing the latter to become abnormally heated and producing weak or bulged spots.

Feed Pumps and Injectors. — The boiler is usually supplied

with water by means of one or more direct-acting steam-pumps. These should preferably be double-acting and duplex (two cylinders), in order to maintain a steady flow of water; and the design should be as simple as possible, so as to reduce the danger of accidental interruption of the water-supply, which is a serious matter. The pumps should be capable of delivering at least twice the quantity of water that corresponds to the maximum steam consumption of the engines in order to have ample margin for leaks of water and steam, blowing off, interruptions, and to enable the steam pressure to be kept down in case of sudden stoppage of the engines. A duplicate pump or an injector should be provided as a precaution against breakdowns. The pump should be regulated to feed at exactly the right rate, so that it keeps a uniform stream of water flowing into the boiler through the heater; whereas, if the pump is stopped part of the time, the water in the heater will get too hot, and when the pump is started again at increased speed, to make up for the stoppage, it then tends to fill the boiler with cold water. The feed-pipe leading into the boiler should be arranged to give the feed-water a motion in the same direction as the natural circulation of the main body of water in the boiler, thereby aiding the flow.

There should be both a check-valve and a stop-valve between the boiler and pump. Without a check in the pipe the hot water is likely to back up on the pump and make it difficult to start; and they are also needed in case of accident or repair. A safety blow-off should also be provided to prevent blowing out of packing or bursting of pipe.

The most necessary condition to the satisfactory working of the steam-pump is a full and steady supply of water. The pipe-connection should in no case be smaller than the openings in the pump. The suction-lift and delivery-pipes should be as straight and smooth on the inside as possible, and the total area of the strainer-holes should be from three to five times the area of the pipe.

When the lift of a pump is high, or the suction long, a foot-valve should be placed on the end of the suction-pipe, and the area of the foot-valve should exceed the area of the pipe. A foot-valve enables the pump to start off promptly and freely, as it avoids waiting for the suction-pipe to fill.

The suction-pipe should be air-tight, because any considerable leakage of air would prevent the flow of water. A slight leakage, however, is sometimes permitted to avoid pounding and does no harm if the pump has ample capacity. It is important for the suction-pipe to be as straight and free as possible.

The area of the steam- and exhaust-pipes should in all cases be fully as large as the nipples in the pump to which they are attached. The cylinders of steam-pumps should always be oiled before starting in the morning or stopping at night. In the ordinary boiler feed-pump the ratio between steam- and water-cylinders is about four to one in area, or two to one in diameter. Stuffing-boxes on the piston- and valve-rods should in all cases be filled with soft, moist packing, because packing which is allowed to become hard and dry will flute the rods, inducing leakage and necessitating repairs. The air-vessels on the delivery-pipe of the steam-pump should never be less than five times the volume of the water-cylinder.

It is almost always advantageous, and at high speeds necessary, to connect a vacuum chamber to the suction-pipe near the pump, to avoid shock, particularly with long suction-pipes.

When pumps are stopped or are put out of service in cold weather, all the drain, drip, and pet cocks should be left open, and the steam-cylinder should be well oiled before stopping. Ordinarily the speed of the piston or plunger is between 50 and 100 feet per minute, depending upon the style of pumping, the piping, etc., but should be low enough to avoid pounding and excessive wear.

A steam-injector capable of feeding all the boilers should be provided in addition to the feed-pump, for use in case the latter fails. It is not desirable to use injectors all the time, however, since they are more wasteful of steam than a pump, especially if a condenser be employed in the plant, and the exhaust from the pump is run into it; or in case the exhaust is used for heating.

Feed-water Heaters.—These should be provided in every electric-lighting installation, whether it be a large central station or a small isolated plant, in order to save as much as possible of the heat in the exhaust steam, and at the same time avoid feeding the boiler with cold water. The ordinary forms of feed-water heater consist either of a collection of pipes through which the

feed-water is passed, and around which the exhaust steam from the engine circulates, thereby warming the feed-water, or the converse arrangement. The feed-water heater introduces no objectionable complication or trouble, being merely interposed in the pipe leading from the feed-pump to the boiler; and it seems to be generally desirable and advantageous for both condensing and non-condensing engines, even when the exhaust steam from the latter is used for steam heating. The Berryman heater is a well-known type, and consists of a series of inverted U tubes, through which the exhaust steam passes, and around which the feed-water circulates.

Economizers.—These, like feed-water heaters, have for their object the saving of escaping heat and the warming of the feed-

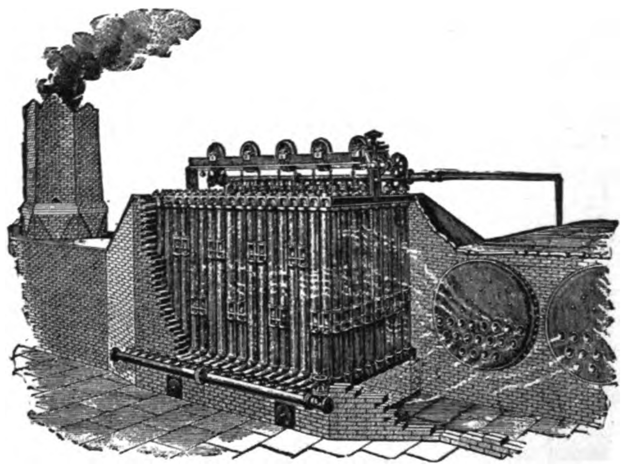


Fig. 22. Green Fuel Economizer.

water; but in the economizer the heat is obtained from the waste gases on their way from the boiler to the chimney, instead of from the exhaust steam. The form and arrangement of the Green economizer, which is extensively used in this country and abroad, is shown in Fig. 22. The economizer of course tends to reduce the temperature of the gases in the chimney, and to that extent decreases the force of the draught. If, however, the gases leave the boiler at a higher temperature than is needed to give sufficient draught, then the reduction in temperature is not objectionable. If, on the other hand, the gases are cooled by passing through the

boiler to as low a temperature as is compatible with a good draught, then the economizer evidently is undesirable, unless used in combination with mechanical draught. As a matter of fact, the economizer is practically an extension of the boiler; but the use of a separate economizer is a much better arrangement than combining it directly with the latter (by making a longer boiler, for example), since it enables the boiler as a whole to be run at a higher temperature and pressure, and avoids the introduction of cold water into the boiler proper. It would therefore seem that the economizer is particularly suited to cases where the steam pressure is high, since the temperature of the boiler, and that of the waste gases leaving the boiler, would be correspondingly elevated. This and other forms of economizer are very commonly adopted in electric-lighting plants, and are usually to be recommended, particularly when the steam pressure is 100 lbs. per square inch, or more.

Since the feed-water heater utilizes the heat in the exhaust steam it cannot raise the temperature of the water above 212° F. On the other hand, the economizer derives its heat from the waste gases, which may be at 500° or 600° F., so that the feed-water is brought above the boiling point and is under full boiler pressure. Hence the water must pass through the feed-pump before entering the economizer. The feed-water heater may also be placed on the same side of the pump, in which case it carries boiler pressure and the pump works on cool water. If the pump is put between the heater and the economizer the former runs at ordinary pressure and the pump contains warm water, but below boiling point.

ARRANGEMENT OF BOILERS.

The vital importance in electric lighting of avoiding the least interruption in service, makes it necessary to take every precaution to insure absolute continuity in the working of the plant as a whole, even if an accident should occur to any one element. This is usually secured by having at least one, and if possible two or three, extra or reserve elements of each kind. In addition to having spare apparatus, it is also necessary to adopt a carefully considered arrangement, in order that the breaking down of one element shall not prevent the use of the

others. For example, if a number of boilers connect with one main steam pipe, it might happen that an accident to that pipe at some point would cut off the supply of steam from all of the boilers. One way to provide against this trouble is to have what is called the "ring" arrangement of boilers, in which the boilers are placed in two rows and the main steam pipe is a complete ring, so that accidents would have to occur simultaneously at two points in order to cut off any considerable number of boilers. There is a valve between each boiler and the ring pipe, and also one in the latter between each boiler and the next. This arrangement is an excellent one, and is often adopted. The arrangement consisting of a duplicate set of steam-piping is an almost sure guaranty of continuity of service; but it involves considerable extra expense and complication. An example of this arrangement is found in the plant of the Westchester Lighting Company at New Rochelle, N. Y., described in the *American Electrician*, March, 1902. In this case every boiler is connected so as to feed into either of two duplicate 16-inch steam headers. The two larger engines of 750 H. P. each are individually fed through 6-inch pipes from one header only, being supplemented by additional connections through reducing valves to the low-pressure cylinders from the other main header. The other three engines, aggregating about 400 H. P., and all of the auxiliaries are fed in duplicate from the two headers.

Partial or complete duplication of steam-piping is particularly important where the boilers and engines are not very close together because a breakdown is more likely to occur. If the boilers are placed in a row on one side of the division wall and the engines similarly located on the other side, with one common interconnecting steam header, practically the same advantages may be secured without duplication. The piping of the New York Edison Company's Waterside Station is so arranged, as shown in plan in Fig. 23, also on pages 48 and 49. All of the delivery pipes from the boilers and all of the pipes feeding the engines are connected directly to a single longitudinal header, each of these pipes being controlled by its own valve. There are also valves in the header by which it may be subdivided so that an accident at one or even two or three points would not disable the entire plant. On the other hand, an accident in the middle of the

header will prevent engines at one end being operated by boilers at the other end of the row, which is possible with duplicate piping. But with like units it makes little difference which are in operation. Sometimes each engine is supplied with steam from an independent group of boilers, forming the "group-system."

Steam-Piping.—This matter is one of those details of construction which are very commonly neglected, and cause far more trouble than the principal elements of a plant. The pipe used should be of the best quality, made either of wrought iron or steel, lap-welded and of ample thickness to stand the pressure. Flanges and fittings should be made of the best material and

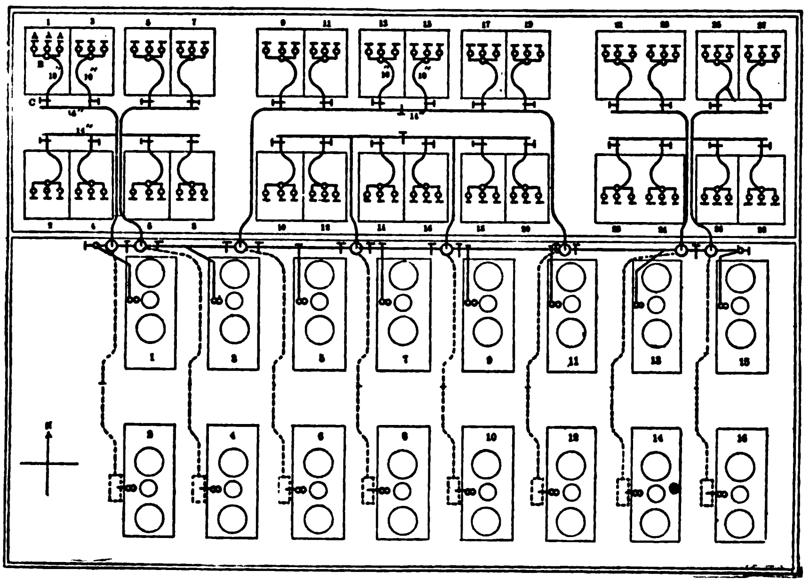


Fig. 23. Steam-Piping of New York Edison Waterside Station.

very carefully put together. Leaky steam-fittings are very common and cause much annoyance. The flange may be recessed or grooved to prevent blowing out of the gasket. The best construction is to have the flanges welded on to the ends of the pipes. This involves greater expense in making and fitting, but would probably save money in a permanent plant. Ordinarily the flange is screwed upon the pipe, in which case care should be exercised to have exactly the same taper on both, which is a very essential condition to a tight joint. The joint is calked on the

inside, and the small recess in the back of the flange around the body of the pipe is calked with Babbit or steam metal, in case of leakage of the screw-joint when circumstances will not permit the joint to be opened and recalked inside. The screw-joint should be made with plumbago, to allow it to be unscrewed, if necessary, without breaking. The flange should be very heavy and made as strong at the bolt-holes as at other points, which is secured by having bosses around the latter. The bolts should be as close together as the free use of the wrench will permit.

Steam-piping should be carefully arranged so that water will not collect in it, as it causes water-hammer effects, and if it gets into the engine cylinder it may wreck it. One plan is to have the pipe slope slightly downward all the way from the engine to the boiler; but the difficulty is that the steam tends to stop the back flow of the water and carry it along with it. It is better, therefore, to have the piping slope toward the engine, and insert a steam trap or separator near the latter to eliminate the water. The latest and best practice consists in running a small pipe immediately beneath the main pipe or steam header, the two being connected at frequent intervals by short vertical pipes. These auxiliary pipes are sometimes made as small as 1 inch, but 1½ inches in diameter is better practice. This drainage pipe is connected to a steam trap, returned to the boiler or otherwise arranged so that the water condensed from the steam is continually drawn off from the header. With sufficient height in the boiler-room it is desirable to have vertical bends (Fig. 24) connecting the boilers with the header in order to avoid the "pocketing" or retention of the water. For a similar reason the connections to the engines may be taken from the upper side of the header.

Gaskets.—Corrugated gaskets of copper may be used in the case of mains where the ends of the pipe can be freely moved, or sometimes they may be omitted altogether in such a case, and the joint made iron to iron. But in the case of repairs, which are sure to come sooner or later, the line will be distorted more or less, and it will be almost impossible to bring the ends back to exactly the same position. For this reason it is better to use a thin composition gasket. This will allow for slight inequality in the faces and fitting of the flanges.

Expansion Joints.—The ordinary slip-joint is not suited to high pressure, because it will not slide if the packing is adjusted tightly enough to prevent leaking. The best way to take up

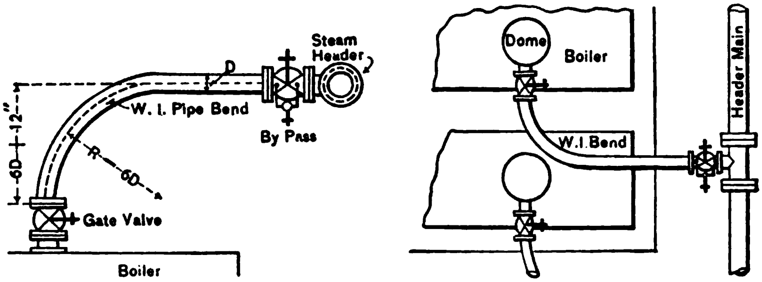


Fig. 24. Vertical and Horizontal Pipe-bends.

expansion in high-pressure systems is by means of long pipe-bends of considerable radius, the proper proportions being shown in Fig. 24.

Valves.—These should be globe or gate valves, operated by an outside screw. The spindle should be of steel, and tinned, or of brass. The valve body should be extra heavy for high pressures, and in all cases stiffer than any other part of the system, to prevent any springing, which would cause the valve to leak. The seats of the valves should be bronze or brass. All valves with over 6 inches diameter of port should have a by-pass valve (i.e., a smaller valve about 1½ to 2½ inches in diameter) to equalize the pressure on both sides of the large valve before it is opened. This relieves excessive strain on the spindle and seats, and should always be used on high-pressure work. Large valves or those that are inaccessible may be opened and closed by motors.

Supports for Steam-Piping.—A steam pipe should rest when possible upon some solid support, and is often mounted upon rollers to allow for expansion. It is very important to avoid vibration, which often occurs, as well as the strains due to expansion, because they rack the whole system and cause leaky joints. Rollers often give trouble on account of rust, so that many engineers provide simple flat iron surfaces upon which the pipe rests. If supported from overhead beams, some good form of pipe-hanger

is used, which should be carefully adjusted so as to preserve the alignment of the pipe, and at the same time long enough with a flexible joint to allow for expansion. One of the best arrangements is to have all the piping below the engine-room floor in the spaces between the foundations of the machinery. This permits the pipes to be placed on solid supports, connections to the engines being made by risers with a steam-separator at the base of each.

Steam Pipe Covering.—All pipes carrying live steam should be carefully covered with some material, to prevent loss of heat and condensation of the steam. Various materials are used for this purpose, such as mineral or slag wool, magnesia, asbestos, hair felt, and other similar substances. It is preferable that the material should be incombustible. Several dealers make a specialty of supplying these coverings in various forms to fit different sizes and shapes of steam-piping, elbows, valves, etc. These are usually held in place by thin metal straps, and when properly put on, and painted or whitewashed, they present a very neat appearance. The covering may also be applied in the form of plaster.

Good pipe covering effects a very considerable saving by reducing condensation. The loss of heat varies with the temperature (i.e. steam pressure), size and position of pipe and other conditions, being usually given as 400 to 800 heat-units (lb.-Fahr.) per square foot of bare pipe. The use of covering saves from 80 to 90 per cent of this loss, depending upon the thickness and nature of the material.

For more detailed facts regarding steam-piping, see *The American Electrician* of 1902 and 1903, which contains a series of articles describing electrical stations, the arrangement of boilers, engines, and piping being made a prominent feature. In the issue of December, 1902, there is a paper by H. G. Stott on steam pipe covering which gives the results of comparative tests on different materials. The same subject is discussed by G. H. Barrus in the *Trans. Am. Soc. Mech. Eng.*, May, 1902.

Steam-Separators.—It is of the utmost importance that steam supplied to an engine should be as *dry* as possible. The significance of this is that steam or any other true vapor is made up of

separate molecules, and is as transparent as air ; but if small particles of water are present which have either been condensed or have not been evaporated, then it contains a larger amount of water than saturated vapor at that temperature and pressure. It then becomes cloudy, since the particles of water that are present, though very small, are infinitely large compared to a molecule, and they intercept or reflect light. Tests of the percentage of moisture in steam, which usually varies from 1 to 10 per cent, can be made in various ways, a thorough method being described in the report of a committee on boiler tests in Volume VI. of the *Transactions of the American Society of Mechanical Engineers ;* but this is rather too elaborate and difficult for ordinary work. A simple method to approximately determinate the dryness of steam consists in allowing a small jet to escape, and if it is transparent close to the orifice, or even a grayish-white color, the excess of moisture is probably less than 1 per cent. If the jet is strongly white close to the orifice, the excess of water is probably 2 per cent, or more. In making this test the steam should not be allowed to travel far in a naked pipe, because it tends to be condensed. Steam containing not more than 3 per cent of moisture is considered fairly "dry." The objections to wet steam are that it introduces water into the cylinder, which might wreck the engine ; it also increases cylinder condensation, and reduces the efficiency and output of the engine. It is therefore a requirement of a good steam-boiler that it should produce steam which is as dry as possible. This is secured by proper design, being largely dependent upon an ample surface for the disengagement of steam, and a sufficient steam space or reservoir in the boiler. If steam rises from a surface of water with a velocity greater than 2½ to 3 feet per second, it carries water with it in the form of spray. This velocity may be calculated by dividing the total volume in cubic feet per second of steam produced by the total surface in square feet from which it rises. When the boiler throws a large amount of water into the steam it is called "priming," and may be due to impure water that forms bubbles and foam, improper design of the boiler, or too high a water-level, which latter will reduce the steam space and bring the surface too near the outlet.

The best way to obtain dry steam is, of course, to have the boiler generate it in the first place ; but in case the boiler gives wet steam, either from improper design or impure water, or because it happens to be working badly (which might occur in almost any boiler), then it is very important to remove the water from the steam before it enters the cylinder. There is also some condensation of steam in the piping, especially if the engines are not very close to the boilers. The means ordinarily employed to eliminate water from steam consists of a steam-separator. An efficient one, of the centrifugal type, is shown in Fig. 25. The principle of this and other separators is to inter-

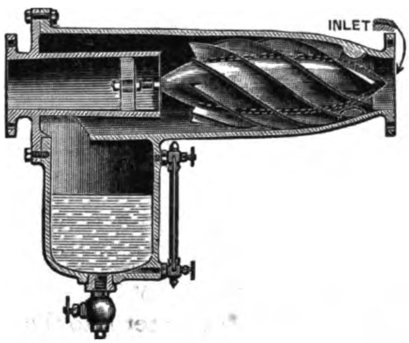


Fig. 25. De Rycke Steam-separator.

rupt the direct flow of the steam and give the particles of moisture an opportunity to settle and collect in a receptacle. The curve blades shown are designed to facilitate the separation by throwing the moisture particles against the sides of the vessel by centrifugal force. Steam-separators should be placed as near as possible to the steam inlet of the engine.

Management of Boilers.—Steam boilers, being the most important and most dangerous element in an electric lighting plant, should receive the greatest possible care, and particular attention should be given to the following points, to insure *safety:*

Safety-Valves.—These should be of ample size, and in perfect working order. Neglect or overloading might lead to the most disastrous results. They should be tried at least once every day, to see that they act freely.

Pressure-Gauge. — This must be absolutely accurate; and if there is the slightest doubt about it, it should be compared with a standard gauge. It should stand at zero when the pressure is off, and should show the same pressure as that for which the safety-valve is set, when the latter is blowing off.

Water-Level. — The engineer should make absolutely sure that the water is at the proper height in starting up, or at the beginning of each watch. The glass gauges should not be relied upon entirely; but the gauge-cocks should be tried, because the passages in glass gauges are apt to become clogged and give a false indication of the height of the water, which might be much lower or higher than that in the glass tube.

Low Water. — In case the water-level falls too low in the boiler, immediately cover the fire with ashes (wet if possible) or earth. If nothing else is handy, use fresh coal, taking great care, however, to put on a sufficient amount to deaden, and not to increase, the fire. Draw the fire as soon as it can be done without increasing the heat. Do not turn on the feed-water, start or stop the engine, or lift the safety-valve, until the fires are out and the boiler cooled down.

Blisters and Cracks. — Either are likely to develop even in the best plate-iron; but at the first indication they should be carefully examined, and the boiler put out of service and repaired.

Fusible Plugs. — If used, these should be examined when the boiler is cleaned, and carefully scraped clean on both the water and fire sides.

The attention required to secure *economy* is as follows: —

Firing. — The coal should be thrown on evenly and regularly, a little at a time. Moderately thick fires are most economical, but thin fires must be used when the draught is poor. The grate should be kept evenly covered, and no air-holes in the fire allowed to form.

Cleaning. — All heating-surfaces must be kept clean inside and out, to avoid serious waste of fuel. The frequency of cleaning depends upon the nature of fuel and water. As a rule, not over $\frac{1}{16}$ or $\frac{1}{8}$ inch of scale or soot should be permitted to collect on the surfaces before cleaning.

Foaming and Priming. — This can usually be checked by reducing the outflow of steam, or by decreasing the draught of the

fires. Slightly opening the blow-off and increasing the feed will remove impure water. The water-level may be lowered if high enough to permit of it.

Blowing off. — If feed-water is muddy or salt, blow off a portion frequently, according to condition of the water. The boiler should be emptied every week or two, and filled up entirely fresh; but the boiler should not be emptied while the brickwork is hot.

Durability. — Deterioration or injury to boilers is avoided by general care; certain special points may be noted: Cold water should not be put into a hot boiler; dampness should not be allowed on the outside of the boiler, as it tends to corrode and weaken it; the boiler should not be fired up too rapidly or too intensely. If a boiler is not required for some time, it should be emptied and dried thoroughly. If this cannot be done, it should be filled with water, into which is put a quantity of common washing-soda.

Testing Steam-Boilers. — Tests of steam-boilers* are made to determine the quantity and quality of steam that they supply, the weight of fuel required to produce a certain amount of steam, and other similar facts. A boiler-test requires considerable knowledge, care, and skill, as well as accurate apparatus.

The principal points to be ascertained and noted in a boiler-test are: —

1. The type and dimensions of the boiler, including the area of heating-surface, steam and water space, area of water surface, and draft area through or between tubes or flues.

2. The kind and size of furnace; area of grate, with proportion of air-spaces in it, height and size of chimney, length and area of flues.

3. Kind and quality of fuel, and amount of ash and water therein. The latter is a more important item than is generally understood, as it not only adds to the weight without increasing the value of the fuel, but the heat taken to evaporate and send the steam up the chimney in a highly superheated condition adds to the unobserved waste.

4. Temperatures of external air, of fire-room, of chimney gases, of fuel, of water, and of steam.

5. Pressures of the steam, of barometer, and of draught in chimney.

6. Weights of feed-water, of fuel, and of ashes. Water-meters are not reliable as an accurate measure of feed-water.

7. Time of starting and of stopping test, taking care that the observed conditions are the same at each as far as possible.

* This subject will be found very fully treated in the report of a committee to the American Society of Mechanical Engineers, and the discussions on the same. *Transactions A. S. M. E.*, vol. xx.

8. The quality of the steam, whether "wet," "dry," or "superheated."

From these data all the results can be calculated, giving the economy and capacity of the boiler, and the sufficiency or insufficiency of the conditions, for obtaining the best results.

The amount of water evaporated per pound of coal is universally conceded to be the proper measure of the efficiency of a boiler; but in order to compare one boiler with another, each should have equally good coal, be fed with water at the same temperature, and furnish steam at the same pressure. As this is impracticable in testing, a standard has been accepted to which all tests should be brought for comparison. This is called the "equivalent evaporation from and at 212°" per pound of combustible; that is, what the evaporation would have been if the coal had been without ash, the feed-water at boiling-point, and the steam delivered at atmospheric pressure.

It may be determined by the following formulæ: —

Let W = the observed evaporation per lb. of combustible.
t = the observed temperature of feed.
T = the temperature of steam at observed pressure.
H = the total heat of steam at the observed pressure.
W' = equivalent evaporation from and at 212°.

$$W' = W\left(1 + \frac{0.3\,(T - 212) + (212 - t)}{966}\right);$$

$$\text{or,} \ldots \quad W' = W \times \frac{H + 32 - t}{966}.$$

The value of T and H may be found in the table on page 92.

Steam-Boiler Economy. — Correct design, construction, and management of the boiler-plant is a most important item in an electric-light station. Forcing the boilers beyond their capacity, wastefulness in the use of coal, or other such loss, might result in the financial ruin of the entire enterprise. On the other hand, raising the evaporation from 7 to 8 lbs. of water per lb. of coal, represents a saving of about 14 per cent, which would warrant an expenditure for improvements equal to one year's coal-bill, since it would pay 14 per cent on the investment.

Claims are often made as high as 11 or 12 lbs. of water evaporated per lb. of coal; but in regular practice it is difficult to do better than 10 lbs., and even 9 lbs. is a very good ordinary result.

Boilers are rated on the basis of 30 lbs. of water evaporated per H.P.-hour, at 70 lbs. pressure, feed-water being 100° F.; but this rating is nominal because good engines do not require so much. Under very favorable conditions the best engines consume only 10 lbs. of steam per H.P.-hour and 12 lbs. in regular service. Assuming that 15 lbs. can be realized in good practice, the actual H.P. of a boiler is twice the rated value.

CHAPTER X.

STEAM-ENGINES FOR ELECTRIC LIGHTING. GENERAL CONSTRUCTION.

Classification. — Engines may be divided into various classes for convenience of reference, according to their form, action, or purpose. For example, engines are either *horizontal*, *vertical*, or, in rare instances, *inclined*, according to the position of the cylinder or cylinders.

An important distinction, particularly in engines used for electric lighting, exists between *low-speed* and *high-speed* engines. It is impossible to draw a definite line between the two classes; but in a general way it may be said that low-speed engines usually run at less than 150 revolutions per minute, the ordinary speed being from 50 to 100, whereas the customary rate of high-speed engines is from 200 to 350 turns per minute.

Engines may also be divided into classes, depending upon the important matter of speed governors. There are *throttle* and automatic *cut-off* governors. With the former, the speed is controlled by partially shutting off and reducing the pressure of the steam allowed to enter the cylinder. In the latter, the steam enters the cylinder at approximately the full boiler pressure; but the governor causes the supply to be entirely cut off at a certain fraction of the stroke, depending upon the speed of the engine.

Engines are divided into *simple* and *compound*, according to whether the steam expands completely in one cylinder, or partially expands in one cylinder, and then passes to another cylinder or cylinders, in which it is further expanded. Engines are called *compound*, *triple*, or *quadruple expansion*, according to whether the steam is expanded twice, three times, or four times, respectively.

GENERAL CONSTRUCTION OF STEAM-ENGINES.

The general construction of steam-engines will be considered in the present chapter, and then the special discussion of the various typical forms will be taken up in the next chapter.

The principal parts of a steam-engine are the cylinder, piston, piston-rod, valve, governor, mechanism connecting the piston-rod and fly-wheel, fly-wheel, bearings, and the base or frame supporting all these various parts.

The Cylinder. — This is usually a simple cylinder of cast iron, accurately bored inside, and ending in faced flanges, to which the ends or covers are bolted. Since the cylinder has to withstand the internal pressure of the steam, it should be of sufficient thickness; but usually its strength far exceeds that required to sustain the steam-pressure, for the reason that, being made of cast iron, it can be quite thick without involving any considerable expense; and it is also desirable to have it of ample thickness, in order to allow it to be re-bored when worn, and to prevent it from bending or warping to the least extent by the very heavy mechanical strains to which it is subjected. One end of the cylinder is provided with a stuffing-box, which allows the piston-rod to slide freely back and forth, but prevents the steam from leaking out. At the two extreme ends of the cylinder are the ports, through which the steam alternately enters and leaves the cylinder. These ports are connected by suitable passages to the steam-chest, in which works the valve which controls the inlet and outlet of the steam.

The principal points to be observed in designing steam-cylinders are, the proper proportions and thickness of the various parts to give ample strength, and the perfect boring and fitting of the same. The proper length and diameter of the cylinder depend upon circumstances, and considerable difference of opinion in regard to this question exists among authorities and builders. Ordinarily the stroke of an engine is from $1\frac{1}{2}$ to $2\frac{1}{2}$ times the diameter of the piston. The length of the cylinder must, of course, be equal to the stroke plus the thickness of the piston and the clearances at both ends. Usually the total length of the interior of the cylinder is about twice the diameter.

Sometimes cylinders are "jacketed;" that is, surrounded with a space which is filled with steam in order to warm the cylinder itself. Steam-jackets are rarely used, however, except in cases where the steam-pressure, and therefore temperature, is very high, or the ranges of temperature very great. Its complication and cost of construction are the principal objections to it.

Some covering of nonconducting material, such as wood or felt, called lagging, should be applied to steam-cylinders, in order to reduce the loss of heat, and cylinder condensation.

The Piston is the part which is driven back and forth in the cylinder by the pressure of the steam; and from it the entire power of the steam is obtained, its area multiplied by the steam-pressure per unit of area being the total pressure exerted upon it. If the piston were driven by a constant steam-pressure, it would be desirable to make it as light as possible, to avoid wear and the effect of its inertia at the ends of the stroke. But in all economical engines the pressure varies greatly, because the steam is cut off and acts expansively during the greater part of the stroke; hence it is customary to design the piston to have sufficient weight so that its inertia takes up the excessive pressure of the steam in the beginning, and gives up energy toward the end of the stroke, when the pressure is low, thus aiding the compression of the steam on the other side of the piston. The piston is made steam-tight in the cylinder in various ways, the usual plan being to surround it with split rings of cast iron, steel, or gun metal, which are made to have a tendency to spring outward slightly, and thus fit closely against the walls of the cylinder. Two or more of these rings are placed side by side, and arranged so that the joints are not in the same line. These rings are held in place by recesses or grooves turned in the periphery of the piston. The relative diameter and thickness of pistons depend on the particular type of engine, the advantage of a long piston being that it tends to diminish leakage and wear, and it can be made hollow, so that it is not very heavy; but it necessitates an increase in the total length of the cylinder. *The piston-rod* is usually made of steel, and is connected rigidly to the piston by a shoulder formed upon it, and a nut at its end.

The Stuffing-Box prevents the leakage of steam around the piston-rod. It consists simply of a cylindrical projection cast on the cylinder cover, its internal diameter being somewhat larger than the piston-rod which it contains. The space between is filled with some form of packing, which is held in place and adjusted by a loose piece termed the *gland*. The gland is attached to a flange at the outer end of the stuffing-box by suitable bolts and nuts. An almost infinite number of devices and materials

have been employed as packing in stuffing-boxes. The ordinary kinds used are hemp, asbestus, or some other fibrous material mixed with tallow, india rubber, etc., to make it steam-tight. Graphite, fine particles or shavings of metal, and similar substances, have also been employed in packing. These soft packings are usually applied either in the form of rings or rope, the latter being wound spirally around the piston-rod. Rings of Babbitt or other metal are also used. The packing of the piston often causes annoyance, since it is very likely to be either too tight or too loose, and wears so rapidly that it requires constant adjustment.

Valves. — The most delicate parts of a steam-engine are the valves, and the mechanism which operates them. The function of the valves is to control the entrance and exit of the steam to and from the cylinder, so that each shall occur at exactly the right moment, and continue for exactly the proper period of time. Four kinds of valves are very commonly used in steam-engines, these being *ordinary flat slide valves*, *cylindrical slide* or *piston valves*, *rotary valves*, and *poppet valves*. The advantage of the flat slide valve is that it is readily fitted, and a certain amount of wear can occur without causing leakage or requiring refitting. It has the disadvantage, however, that it is difficult to balance; that is to say, the steam tends to force it against its seat with excessive pressure. The advantages of the piston valve are that it is easily balanced, so that the pressure caused by the steam is equal in all directions; and for a given sized valve a large opening of port is obtained with a small motion, since the port can extend all the way around. The objection to a piston valve is the fact that wear makes it smaller than the cylinder in which it works, so that it is apt to leak. There are three methods of refitting: a new and larger piston; the valve-seat bored out and a bushing inserted which fits the worn piston; or a special device provided to take up the wear. In the Mackintosh and Seymour horizontal, high-speed engine the seat is split and can be contracted by an adjusting-screw (page 169). The rotary valve has advantages similar to those of the piston valve; in fact, an even smaller motion will cause a large opening of the port, but it is also difficult to adjust for wear. Rotary valves have, however, long been used very successfully in the Corliss types of engine.

Valve Gear.—The valves are caused to open and close in

almost all types of engines by one or more eccentrics placed upon the main shaft of the engine. The eccentric is practically a form of crank with the crank-pin enlarged sufficiently to include the main shaft within its section. It ordinarily consists of a sheave

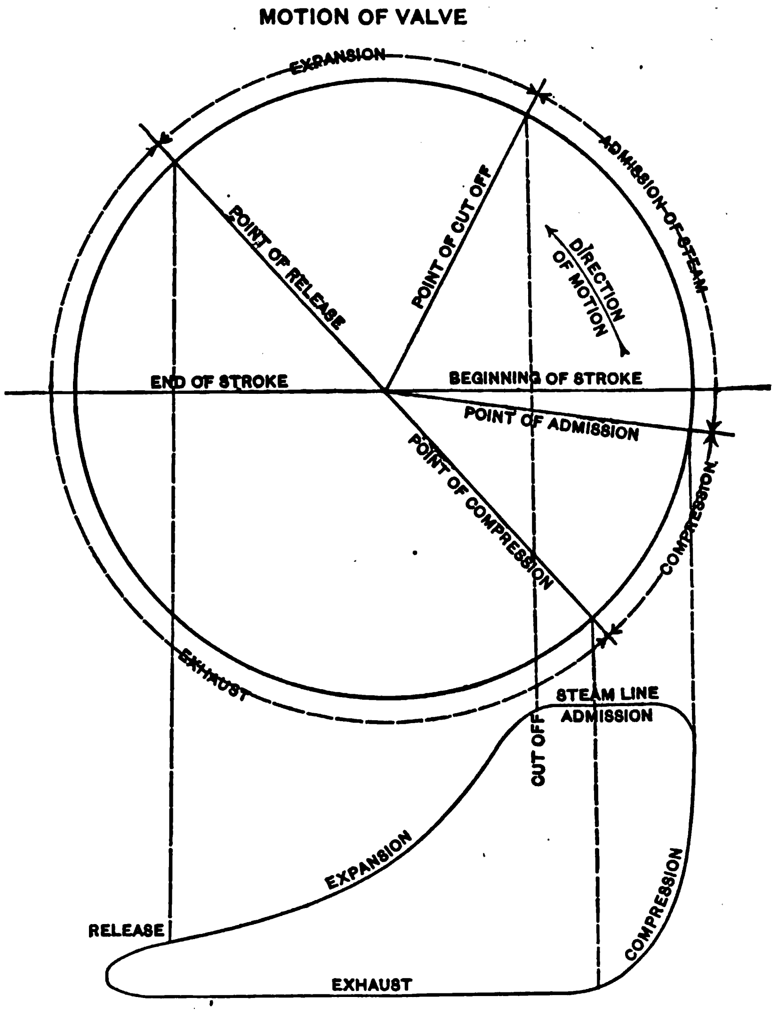


Fig. 26. Action of Valve and Steam.

or disk of cast iron surrounded by a strap or ring which connects it with the eccentric rod, the latter being connected directly or indirectly to the valves. When the main shaft revolves, the

eccentric automatically opens and closes the valve. It is possible by one simple eccentric and slide-valve to obtain quite a perfect action of steam in the cylinder. This is done by proportioning

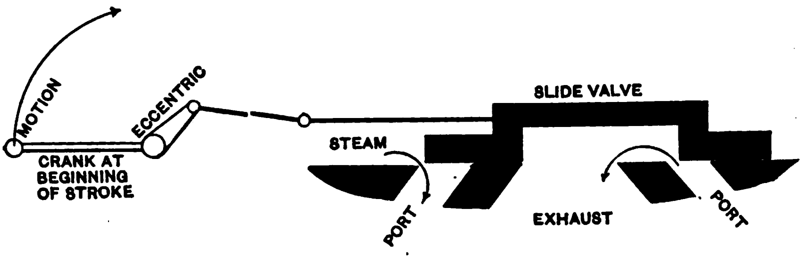


Fig. 27. Lead of Valve.

and adjusting the position and throw of the eccentric, and the relative widths of the ports and faces of the valve, in such a way that the valve opens slightly just before the commencement of each

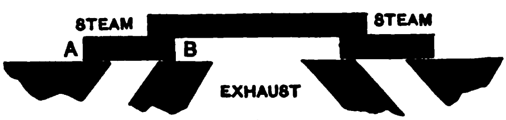


Fig. 28. Lap of Valve.

stroke, in order to obtain full pressure in the cylinder. The amount of this opening, called the *lead*, is secured by setting the eccentric a little more than 90° in advance of the crank, as represented in Fig. 27. The faces of the valve are also made wider than the steam-port, so that when the valve is in its middle position it overlaps the edges of the port, as represented in Fig. 28. In this way the steam is cut off before the end of the stroke, and then acts expansively, which is necessary to obtain economy. The width of the overlap on the steam or induction edge A, of the valve, is called the *outside lap*, and that on the exhaust or eduction edge B, of the valve, the *inside lap*. The former is usually made greater than the latter, as indicated in Fig. 28, in order that the port shall open sooner and more widely to exhaust than to take steam, which diminishes the back pressure. In other words, it is obviously objectionable to limit the outlet of the steam in the same manner as the inlet. The outside lap necessitates a still further angular advance of the eccentric, with respect to the crank, in order to open the valve at the beginning of the stroke,

as shown in Fig. 27. It is customary, particularly in high-speed engines, to close the exhaust a little before the end of the stroke, and obtain what is called compression, or cushioning, which tends to relieve the shock due to reversing the motion of the piston and other parts. This also raises the steam remaining in the cylinder to a pressure similar to that of the boiler, thus avoiding the impact which would occur if high-pressure steam were suddenly admitted to a space having a pressure only equal to that of the atmosphere. In Fig. 26, the position and action of the valve is represented in the circle above, and the action of the steam in the cylinder is shown in the indicator diagram below. A study and comparison of these will give a clear idea of the principles of valve-action and steam-distribution in engines. The ordinary slide-valve, considering its simplicity, gives a remarkably good action of the steam in the cylinder; but to obtain a really perfect effect, and to cause the admission, cutting off, and the release of the steam, as well as the closing of the exhaust, each to occur at the proper instant, and to enable them to be independently adjusted, it is desirable to separate the valve functions of admission and exhaust of steam. This can be done by the use of two valves driven by separate eccentrics, one acting in the ordinary way to control the general distribution of the steam, and the other operating to cut off the steam at the proper point, or by the use of three or four separate valves, each performing one or more of the functions of the single valve described above.

The special forms of valve-gear for obtaining economy, regulation, and other effects in the working of steam-engines, are best described in connection with the various types of engines which have been developed as a result of years of experience, and in which the valve mechanism is the most important and distinctive feature. These are given in the next chapter.

The Governor. — An engine which always works with a constant load would have a constant speed, provided the steam-pressure did not vary. In practice, however, the load on a steam-engine changes from time to time; and in electric lighting, although these changes are rarely sudden, nevertheless they are very great, since the number of lights in the daytime may be very small, and in the early evening the engine may have to carry its full rated load. The fly-wheel, which will be discussed later, acts

to prevent sudden or transient changes in speed due to variations in the load on, or power of, the engine during a single stroke; but something is required to regulate for changes in load that are permanent, or at least last for several strokes.

The device used to secure this control of speed is called a governor; and it acts either to regulate the supply of steam by changing the opening, to a greater or less extent, of a valve in the main steam-pipe, or by automatically changing the point in the stroke at which the steam is cut off. These two types are called, respectively, *throttle* and *automatic cut-off governors;* and either of them requires to be adjusted to admit just sufficient steam to give the power necessary to maintain practically the same speed, whatever the load may be. The throttle governor was the only one employed up to the time when Corliss invented and introduced his remarkable automatic cut-off valve-gear, that is universally regarded as one of the greatest improvements in steam-engines since the time of Watt, and which to this day is used, with only slight modifications, in many of the largest and best stationary engines in America and Europe.

The throttle type of governor is not usually considered desirable in this country, except in small or unimportant engines. It has the defect that it acts to destroy a portion of the pressure of the steam, or "wire-draw" it. This tends to reduce the efficiency of the engine; but the superheating of the steam which results from its being "wire-drawn" through the throttle-valve almost makes up for the loss of pressure by diminishing cylinder condensation. The Willans engine (see next chapter), which is very commonly used in English lighting-plants, and to a certain extent also in this country, has a simple throttle governor. It is claimed that this engine gives economical results in actual use that are fully equal to, if not better than, those obtained by automatic cut-off engines, probably because the loss, due to diminished pressure, is partly offset by the gain due to superheating, as already stated. Furthermore, stations employing Willans engines usually subdivide the power into a number of units, only a sufficient number of engines being run to properly carry the load, thus making it unnecessary to throttle the steam-supply, since the engines are almost always running at or near full load, and the governors only require to regulate for small

fluctuations. Willans engines are compound or triple expansion, which also tends to make them economical. An automatic cut-off governor, on the other hand, allows the steam to enter the cylinder at full pressure for a certain fraction of a stroke, and then the steam is suddenly cut off. This is theoretically and practically a more economical use of steam, and would seem to be very important in engines working at light load for any considerable portion of the time. But, unfortunately, cylinder condensation (described later in the present chapter) causes great losses, particularly with an early cut-off, which the superheating due to throttling reduces, as we have seen; consequently, the automatic cut-off is not so much better than the throttle governor as it has generally been supposed to be.

The throttle governor is simple in construction, consisting usually of two weights suspended from a vertical spindle caused to revolve by connecting it with the main shaft through gearing or belting. When the speed rises above the proper point, the weights fly out by centrifugal force, which partially shuts the valve in the steam-pipe by means of levers and rods. In the Willans Engine (Fig. 56) the governor is mounted directly on the shaft.

The automatic cut-off governor exists in many different forms, which, however, may be arranged in two classes similar to the foregoing. First, those in which the cut-off is controlled by a centrifugal governor with a vertical spindle, Corliss engines being of this type. Second, those forms of governor which are mounted upon, and revolve with, the main shaft of the engine, and are called *shaft-governors*. This latter type has several very important advantages; being carried by the main shaft, it does not have to be driven by belting or gearing, which involves complication, indirectness, is more or less unsightly, and likely to fail and allow the engine to race. The shaft-governor, being upon the shaft, is directly connected to the eccentric, and thereby controls the action of the valve effectively and conveniently; but a shaft-governor requires a considerable speed of rotation in order to give sufficient centrifugal force to operate it, and is therefore only applicable to high-speed engines of 200 or more revolutions per minute. The shaft-governor contributes more than any other element to the compactness, perfection of regulation, and general success of the high-speed automatic cut-off engines

which have been so very extensively used for electric lighting in America, and are so convenient for small plants.

Any form of governor in order to give perfect regulation, that is, maintain a constant speed, must be designed in accordance with certain mechanical principles. The general condition to be fulfilled is that the governor must move from one limit of its throw to the other with a very small change in speed, usually about 1 or 2 per cent. *This requires that the centrifugal force shall be practically equal to the force due to the spring or weight which opposes the centrifugal force, in every position of the governor-weights.* A governor of this sort is called *isochronous,* since it will only run at one speed; and the slightest excess of speed will cause the weights to fly out to their extreme limit, and either throttle or cut off the steam, so as to bring the speed

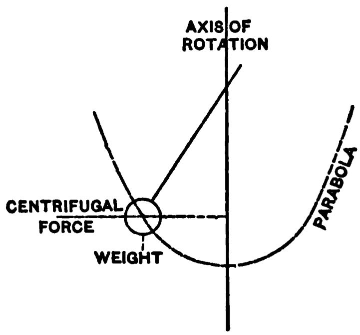


Fig. 29. Theoretical Parabolic Governor.

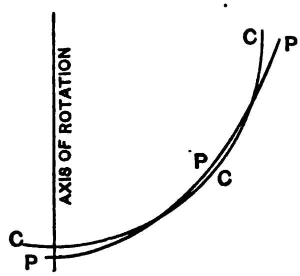


Fig. 30. Practical Governor.

down again to its normal value. Theoretically, if the weights move in the arc of a parabola, as represented in Fig. 29, the effect of the centrifugal force and gravitation is exactly balanced at every point for a certain speed. In practice it would be difficult to arrange the weights to move in a path of this form; and they are therefore suspended by an arm from a pivot, and move in the arc of a circle, *CCC,* which is made to approximate as closely as possible to the ideal parabola, *PPP,* as indicated in Fig. 30. As a matter of fact, the difference is less than that shown in the figure, and the arc of motion is also less; indeed, it is probably better than if the ideal curve could be attained, since a governor which is perfectly isochronous would be too sensitive, tending to shift back and forth from one end of its path to the other.

"Hunting" of Engine-Governors.—The motion of governors which is called "hunting" is usually caused by the fact that the forces are adjusted for nearly perfect synchronism, and if the speed increases, the friction and inertia of the parts prevent them from acting instantly; but when the governor does act, it flies to the limit of its range, and thereby reduces the supply of steam and the speed more than it should. The converse of this action then takes place, and so on, thus causing objectionable fluctuations in speed. Two or more engines driving alternating current-generators in parallel are particularly likely to "hunt," due to surging of the current. This matter is discussed in several papers read before the American Institute of Electrical Engineers, Oct. 25, 1901. Various methods of overcoming the difficulty, which is sometimes very serious, are there considered. The simplest way to prevent hunting of an engine-governor is to provide it with a dashpot, in order to make the motion of the governor gradual and steady. If the governor is too small, the force which it exerts is not sufficient to affect the valve until the speed has changed considerably, which would also cause hunting. This is avoided by making both the centrifugal force of the governor-weights, and the force which balances it, great, so that a small *percentage* of difference between them will have considerable actual value.

For example, if the centrifugal force of the weights at the proper speed is 1,000 lbs., and it is exactly balanced by the force of a large spring, then a variation of 1 per cent in speed will cause a change of about 2 per cent in centrifugal force, which gives an effective force of 20 lbs. to cause the action of the governor. The tendency to hunting is usually greater at very light loads than at half load or more, the effect of the load being to steady the governor.

Another method of securing considerable force to control the valves is to adopt some relay arrangement; that is, the governor proper merely puts a screw or hydraulic mechanism into action. In this way the governor itself may be made small and with little friction; at the same time the force which actually regulates the valve may be considerable. A device of this class is employed to govern the speed of the Curtis steam turbine made by the General Electric Company and described at the end of Chapter XI.

If a spring be employed to give the centripetal force which holds the governor-weights from flying out, isochronism may be obtained by adjusting the length, tension, and angle of the spring so as to balance approximately the centrifugal force in all positions. This can be applied either to the ordinary vertical form of governor, or to a shaft-governor, the latter being always made in this way.

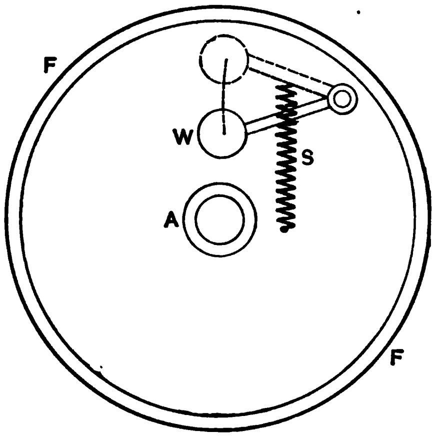


Fig. 31. Principle of Shaft Governor.

The general principle of these latter governors is shown in Fig. 31, in which *FF* is the fly-wheel, rotating on the shaft *A*. The governor-weight *W* is pivoted so that it swings out in practically a radial line from the center of the fly-wheel. The spring *S* is adjusted so that at the innermost position of the weight the spring tension is exactly equal to the centrifugal force at the correct speed. The length of the spring must then be such that its tension increases directly as the distance of the weight from the center increases; that is, when the weight flies out to a position indicated by the dotted lines, and is twice as far from the center, the tension of the spring will then be doubled: and since centrifugal force increases directly with the radius at a constant speed, it follows that the centrifugal force and spring tension will always be balanced at that particular speed. But if the latter falls even slightly, the centrifugal force is less than that of the spring in every position, and the weights move all the way inward, causing the valve to admit more steam, thus keeping up the speed, or *vice versa*. Actual forms of governors are shown in Figs. 48, 54, and other illustrations of Chap. XI.

Dynamometric Governors in which the steam-supply is regulated in proportion to the load transmitted have also been used. These are theoretically more perfect than a centrifugal governor, since the latter requires a change of speed in order to act, and therefore permits the very thing it is intended to prevent;

nevertheless, dynamometric governors have not been successful, probably for the reason that they have the inherent fault of being in unstable equilibrium. Assume, for example, that the speed accidentally increases slightly above the normal, as it is certain to do occasionally, then this excess of speed tends to make the resistance to rotation greater; that is to say, it would have an effect similar to a slight addition of load. This would cause the dynamometer to increase the supply of steam, which would still further augment the speed, and thus the trouble would become aggravated. It would require a speed-governor as a check on the dynamometer, hence the latter is superfluous.

Electromagnetic Governing Devices have been applied to steam-engines with some success; and they would seem to be the best means to regulate engines used for driving dynamos, since they would enable the speed and power of the engine to be directly controlled by the current generated, which the steam-engine governor has for its real and ultimate object. Such a governor is quite simple in principle, and consists of an electromagnet or solenoid fed with current from the dynamo, which is driven by the engine. When the current becomes excessive, the electromagnet attracts its armature against the force of a spring or gravity, and the motion of the armature operates the valve by suitable mechanism, reducing the supply of steam, and thus bringing the speed and current back to the proper point. The coils of the magnet can either have a great many turns of fine wire connected in parallel with the main circuit, to maintain a constant potential, or they may consist of a few turns of large wire connected directly in series with the main circuit for constant-current working. The device is adjusted by varying the pull of the weight or spring.

For a full treatment of the theory and construction of steam-engine governors, the reader is referred to Thurston's *Manual of the Steam Engine*, Part II., pages 360 to 413. The hunting of governed engines is discussed by James Swinburne in a paper with this title read before the British Association, Oxford, 1894.

Connecting-rods are used in engines to connect the piston-rod with the rotating-crank, and act to convert the reciprocating motion of the piston into the rotary motion of the shaft. They

should be made of steel, since they are subjected to considerable strain, due to the push and pull of the piston, and in high-speed engines the up and down throw of the connecting-rod tends to bend it transversely, first one way and then the other, and sometimes breaks it, causing a serious accident. For this reason the connecting-rods of high-speed engines are made of rectangular cross-section, the dimension in the plane of its motion being two or three times the other dimension. The length of the connecting-rod is very rarely less than twice or more than three times the length of stroke. Greater length decreases the obliquity and the side-thrust on the cross-head referred to below, but it makes the rod heavier as well as weaker. The adjustment of the tightness of the connecting-rod end on the crank-pin is one of the troublesome points in handling an engine. If it is too tight, the crank-pin will heat; and if too loose, it will "knock," due to lost motion. A very slight looseness, with barely perceptible knocking, is safest; since a hot crank-pin is far more objectionable than a little noise, and it is impossible to make the proper adjustment while the engine is running.

Cross-heads and Slides. — The cross-head is the name given to the part which connects together the piston-rod and connecting-rod of a steam-engine, and moves back and forth in the slides, thus guiding the outer end of the piston-rod.

In good practice the rubbing surface of the cross-head is such that if V be the velocity (piston speed) in feet per minute, and p be the pressure in pounds per square inch, then * —

$$pV < 60{,}000, \qquad \text{and} \qquad pV > 40{,}000.$$

Piston speeds are usually between 300 and 800 feet per minute, and the allowable pressure is about 60 pounds per square inch for high-speed to 150 for low-speed engines. This p includes the sum of all the pressures forcing the two rubbing surfaces together, but is almost entirely due to the thrust caused by angular position of the connecting-rod with respect to the piston-rod, being zero when the two are in a straight line, and a maximum when the connecting-rod and the crank are at right angles. If the engine turns "over," that is, the crank moves forward in the upper half of its revolution, then the

* Thurston's *Manual of the Steam Engine*, Part II., p. 92.

pressure of the cross-head on the slides is always downward, and the surfaces are easily kept lubricated. But if the crank turns in the opposite direction, — that is, the engine turns "under," — then this pressure is always exerted upward, which renders lubrication much more difficult, since the oil tends to run off of the rubbing surfaces. Nevertheless, on account of the belting,* and for other reasons, engines are sometimes run in a left-handed direction; but it should be avoided if possible.

The Fly-wheel has for its object the maintenance of a steady speed in spite of the variations in action which occur. These variations are of three general kinds: change in the steam-pressure due to expansion, variation in the leverage at which the piston acts on the rotating-crank, and variations in the load on the engine.

In electric lighting, the two former causes of variation must be carefully guarded against, since even slight fluctuations in speed at different parts of the stroke would produce very disagreeable flickering in incandescent lamps. This is often perceptible; and it is possible to count the strokes of the engine by observing the lamps themselves, or a white surface placed near them, the latter being a more sensitive test. The changes in load which occur in electric lighting are gradual if lamps are turned on and off a few at a time, as is ordinarily the case; and the governor of the engine acts to maintain a nearly constant speed. But if a number of lamps are suddenly lighted, in a theater for example, or if a short circuit occurs, the fly-wheel should keep up the speed until the governor has time to act. In practice, however, calculations of the size of the wheel required cover only the first two causes of variation enumerated above; since the sudden changes in load are of indefinite value, particularly in the case of a short circuit, and the fly-wheel is only expected to take care of ordinary fluctuations of this kind.

The weight of fly-wheel required may be determined as follows: —

N = effective horse-power of the engine.
n = number of revolutions per minute.
G = weight of fly-wheel rim in lbs.

* See Chapter XV.

v = mean speed of rim in feet per second.

$$\frac{1}{d} = \frac{v \text{ max.} - v \text{ min.}}{v} = \text{coefficient of fluctuation of speed.}$$

For a single cylinder engine we have, $G = C\dfrac{dN}{v^2 n}$.

The coefficient, C, is dependent upon the point of cut-off, and upon the ratio of the lengths of stroke and connecting-rod. This ratio is usually about $\frac{2}{5}$; and assuming this figure, we have for C the following values:—

	POINT OF CUT-OFF IN FRACTIONS OF STROKE.				
	.10	.15	.20	.25	.33
$C =$	241500	230000	218500	207000	184000

For electric light engines the permissible variation in speed during the stroke should not exceed 1 or 2 per cent, hence the value of d is 50 to 100.

For engines with two cylinders, and having cranks at 90°, the weight of fly wheel required is only about $\frac{1}{3}$ as much as in single-crank engines; and for three-cylinder engines with cranks at 120°, it is still less.

The strength of fly-wheels is a matter of serious importance, since a number of them have burst with disastrous results in electrical plants. These accidents, however, have been more frequent in electric-railway than in electric-lighting stations.

In the *Electrical World* of Oct. 21, 1893, p. 306, an account is given of the bursting of a fly-wheel of an engine in an electric-railway power-station in Brooklyn, New York. This wheel was 18 feet in diameter, and weighed about 20 tons. The station building was partly demolished; and some large fragments, weighing many hundred pounds, crushed through the roof of a house several hundred feet away, the results being sometimes even more serious and far-reaching than those of a boiler explosion.

Fly-wheels were formerly designed on a somewhat rough and incomplete theory of the straining-actions; and to balance the imperfection of the theory, very low working stresses were assumed, but this is not a positive way to secure safety. The ordinary calculations apply to the tension of the rim due to its centrifugal force and to the bending of the arms caused by the acceleration or retardation of the rim, but proper allowance should also be

made for the bending of the rim between the arms and other actions that occur, especially in large or high-speed wheels.

If we consider the fly-wheel to be a simple ring of cast iron, and assume that the effect of centrifugal force is to slightly expand it uniformly in all directions, as indicated in Fig. 32, we have the expression: $f = .097\ v^2$, in which f is the tension in the rim in pounds per square inch, and v is the velocity of the center of the rim in feet per second.

In the case of fly-wheels having teeth or portions of the rim cut away for bolt-holes, etc., the centrifugal force will be practically the same as in a rim of uniform size having the same weight, but the strength will be less; and the expression then becomes, $f = \frac{A}{a}\ .097\ v^2$, in which A is the cross-section of a uniform rim of the same weight and diameter, and a is the actual cross-section at the weakest point. The arms or spokes of the wheel would apparently aid the rim in resisting centrifugal force; but actually their effect is often detrimental, since the rim tends to bulge out between the arms, as indicated in Fig. 33, and is thus subjected to a bending-stress in addition to the tension. This produces a stress which is usually considered to be fifty per cent more severe than the simple tension; but the effects are complicated, and difficult to determine exactly.

The arms are also subjected to a bending-strain due to variations in the velocity of the wheel. For example, the engine must bring the fly-wheel up to full speed in starting; and the acceleration tends to bend the arms, as represented by dotted lines in Fig. 34, assuming the direction of rotation to be right-handed. A similar effect is produced at the beginning of each stroke when the steam-pressure is greatest; and the arms tend to bend in the opposite direction at the end of the stroke when the pressure is much reduced by expansion. These effects are normal, and rarely serious; but much more severe stresses are produced by a short circuit, or the sudden putting on or taking off of heavy loads, and many authorities consider this to be one of the chief causes of fly-wheel accidents.

The greatest twisting force due to any or all causes which it is allowable for the shaft to transmit to the fly-wheel, or *vice versa* through the arms, is given by the formula: $T = nf_a\ Z$.

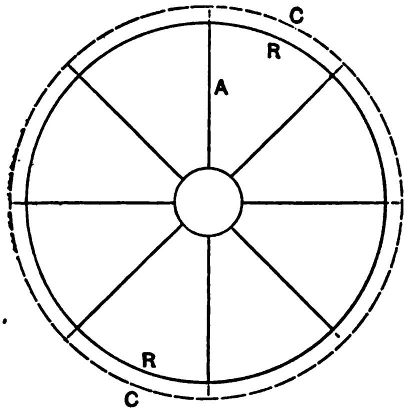


Fig. 32.

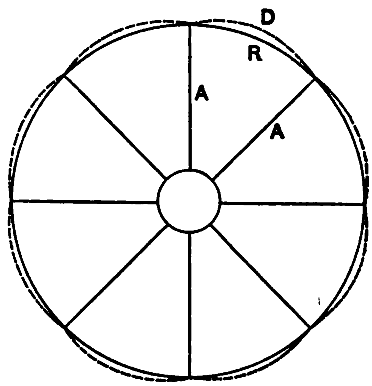


Fig. 33.

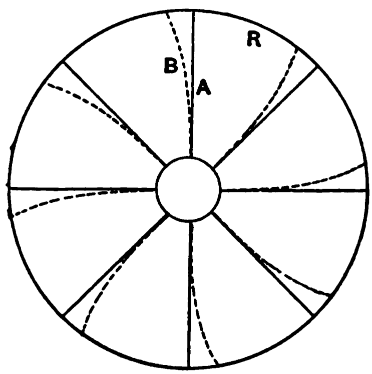


Fig. 34.

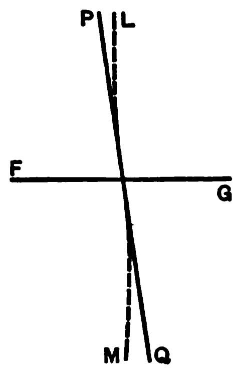


Fig. 35.

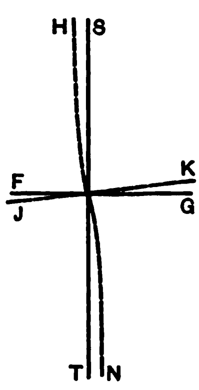


Fig. 36.

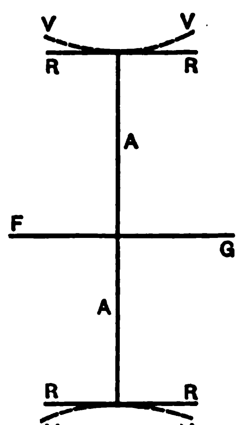


Fig. 37.

Strains in Fly-Wheels.

In this expression T is the maximum twisting movement between the shaft and the fly-wheel rim; n is the number of arms; f_a the safe stress per unit cross-section of the arm due to bending; and Z is the modulus of section of the arm. For a square $Z = \frac{1}{6} b^3$; for a rectangle $Z = \frac{1}{6} ba^2$; for an elliptical section of arm $Z = \frac{\pi}{32} ba^2$, in which a is the dimension of the arm in the plane of rotation, and b at right angles to it.

Another important cause of strains in fly-wheels is that arising from the fact that the plane of the wheel may not be perpendicular to the axis of rotation. It is often stated that this is a gyroscopic action, and that it tends to bend the rim back and forth; but both of these statements are erroneous. In Fig. 35, let FG represent the axis of rotation, and let PQ represent the plane of the fly-wheel, which in this case is improperly mounted upon the shaft, so that it is not perpendicular to the axis FG. When the wheel revolves, it tends to be bent into the form indicated by the dotted line LM; but there is no bending back and forth, since the point P always tends to be bent toward L, and every other point of the wheel always tends to be deflected in the same direction; that is, towards a plane perpendicular to the axis of rotation.

The only way in which there can be gyroscopic action is for the *axis* of rotation FG to be shifted through a certain angle into the position JK in Fig. 36. Then the fly-wheel rotating in the plane ST will strongly resist any deflection from this plane, and will therefore be bent into a form represented by the dotted line HN. If, now, the axis of rotation be brought back to its original position, FG, then the arms of the fly-wheel will be bent back and forth perpendicular to the plane of the wheel, producing a most severe effect. This can occur only when the fly-wheel shaft swings, as, for example, on board ship, or because the bearings are worn too large or are not securely held, thus allowing the shaft to move laterally. Since the angle through which a ship rolls is usually greater than that through which she pitches, it is preferable to have engines and dynamos arranged so that their shafts are fore-and-aft.

Another stress to which the fly-wheels are subjected is represented in Fig. 37, in which FG is the axis and AA the plane of

rotation, *rr* being the rim, which is assumed to be wide and thin. The effect of centrifugal force is to bend the rim into the form *VV*, which adds another bending-force to that shown in Fig. 33, in addition to the simple tension (Fig. 32) of the rim. This trouble may be avoided by making the rim thicker and not so wide, which would not appreciably reduce the moment of inertia; or in case the rim must be made wide, to carry a large belt, it should be supported by two sets of arms, this being a common construction.

It is thought by many engineers that fly-wheels are often ruptured by the actual crushing in of the rim, due to the pressure of the belt in case of a sudden short circuit or overload. It is doubtful, however, if this inward pressure is likely to crush the rim except under most extraordinary conditions; since it is opposed by the centrifugal force, and the rim of the wheel would act as an arch, with great strength to resist any forces directed inward, particularly if they are distributed. A joint or thick spot in the belt would tend to strike the rim a severe blow, and this might break it, especially if aggravated by a short circuit; and of course if the rim be broken at one point the entire wheel would go to pieces. The danger can be avoided by making the rim of considerable radial thickness, and by increasing the number of arms. In some cases the receiving-pulley on the dynamo or line-shaft appears to have yielded in this way, such pulleys usually being made with rather thin rims; and the breaking of the receiving-pulley has caused the failure of the fly-wheel from which it is driven. This might occur either by a fragment being thrown or being carried by the belt against the fly-wheel.

Construction of Fly-Wheels. — In view of the somewhat complicated strains in fly-wheels, and the frequency as well as seriousness of accidents, it behooves the engineer to exercise the greatest possible care in regard to their design, construction, and operation.

The usual practice is to allow not more than 1,000 lbs. per square-inch tension in cast iron, and 5,000 in wrought iron, and to keep the tangential velocity of a cast-iron rim below 100 feet per second. These figures would seem to be amply safe, the factor of safety being considerably greater than is used in most other cases; nevertheless, accidents often occur even with these precautions.

In the accident already cited, which occurred in Brooklyn, the normal velocity of the fly-wheel was only 85.87 feet per second; but this speed must have been far exceeded when the accident occurred, as a much higher initial velocity would be required to carry the fragments to the distances at which they were found. In fact, excessive speed, due to failure of the governor or other cause, is undoubtedly the cause of many fly-wheel accidents; and some arrangement for shutting off the steam in case the engine begins to race is desirable. This may consist of a centrifugal device which automatically closes the throttle-valve by means of a mechanical or electrical connection when the speed rises above the normal. One simple and effective arrangement of this kind comprises an electric motor connected by worm-gearing to an auxiliary throttle-valve. The current for working the motor is obtained from the main circuits of the plant, or from a special dynamo of about one horse-power, the motor being about one-half horse-power. When the circuit which operates the motor is closed, the latter immediately shuts the valve. The closing of the circuit may be effected automatically by a contact device on the governors; and the circuit may also be led to various convenient points, so that it can be closed by hand if the speed becomes excessive. Abnormally high speed, however, will not account for many cases of fly-wheel accidents in which the speed does not seem to have been much above its ordinary value. Moreover, the velocity which is usually allowed is so far below that apparently required to produce rupture, that the speed might be doubled, or even quadrupled, before the actual breaking should take place.

The fact that a cast-iron wheel is likely to have considerable *initial strains*, due to unequal contraction in cooling from the molten state, is probably the reason for the bursting of some wheels which have failed with only a slight increase above normal speed. To avoid or reduce these initial strains, the wheel may be built up of sections which are bolted together, instead of being made of one large casting, in which latter the initial strains may be so great that there is little margin of strength left to resist the centrifugal force.

Another method that has been employed to strengthen cast-iron fly-wheels consists in winding iron or steel wire around the

rim, with sufficient tension to greatly increase its resistance to bursting.

The use of cast steel instead of cast iron for fly-wheels would augment their strength from two to four times; but the cost would also be considerably increased, and would usually be thought excessive. Nevertheless, the higher cost is far less objectionable than danger of bursting. A wooden fly-wheel was made to replace a cast-iron one that burst at the Amoskeag Mills, Manchester, N.H., in 1891. The rim is built up of ash plank arranged to break joints, and fastened together by lag-screws, and also by through bolts. This is claimed to be stronger than a cast-iron fly-wheel; but it would hardly seem that it is the best construction, particularly when we consider that the arms are of cast iron, bolted to the hub and rim, and that the total weight of the wheel is 52 tons, of which only 16 tons are in the rim.

A radical departure from ordinary practice in fly-wheel construction is that used for driving dynamos in the station of the Union Railroad Company of Providence, R. I. (*Power*, April, 1894). This wheel has no arms, but consists of a hub, disk, and rim. The hub is made of cast iron, but the rim and disk are entirely composed of wrought-iron plates riveted together, the total weight being about 40 tons. This construction is expensive, but very strong, and should insure safety at any reasonable speed.

A very complete discussion of fly-wheel theory, construction, and accidents is contained in the issues of *The Electrical World* during October and November, 1894, to which contributions were made by twenty or thirty engineers, including many of the most eminent authorities on the subject.

It has been proposed * to use fly-wheels of considerable weight at high speed to store energy. This might be advantageous for the rapid fluctuations of load in electric railway work, but would not be of much value for the slow variations in electric lighting.

Principles of Condensing-Engines. — Almost any steam-engine can be converted into a condensing one by connecting to it an apparatus in which the steam is cooled and condensed after

* "Possibilities of Securing better Regulation at Central Light and Power Stations by Means of Fly-Wheel Accumulators," a paper read by John Galt before Canadian Electrical Society, September, 1894.

leaving the cylinder instead of being allowed to escape directly into the atmosphere. The advantage obtained is a reduction of the back pressure from that of the atmosphere, which is about 15 lbs. per square inch, down to about 2 to 5 lbs. per square inch, which is as near a perfect vacuum as can be practically maintained in a condenser. Condensation has practically the effect of raising the steam-pressure, since the difference in pressure on the two sides of the piston is augmented about 10 lbs. per square-inch, producing a corresponding increase in the power of the engine. Since this additional effective pressure is gained without drawing any more steam from the boiler, it follows that the efficiency of a condensing-engine is higher, other things being equal. This might also be proved by the fact that the difference between the initial and final temperatures of the steam is increased. (See page 91.)

Condensing-engines are not always desirable, however, since in some cases the disadvantages more than offset the gain. For example, in a small plant the cost as well as increased complication of the condenser and pumps would more than counterbalance the slight saving in back pressure. In a simple (i.e. non-compound) engine it is not desirable to have a great range of temperature because of cylinder losses (page 152), the usual extreme differences in pressure not being more than 80 to 100 lbs.; hence if the steam-pressure has this value it may not be desirable to increase its range by adding a condenser. Moreover, it would probably be easier and cheaper to design the boiler for a higher pressure than to have the complication of a condenser.

This applies to comparatively low pressures of say 80 to 100 lbs.; but if the pressure is already very high, that is, 150 or 200 lbs., then of course it is possible to obtain about 10 lbs. more effective pressure by the use of a condenser without increased danger. The gain, however, is not a very large percentage in the case of such high pressures.

The original reason for using a condenser was the fact that very low steam-pressures were the rule, 15 lbs. being considered high in the time of Watt about one hundred years ago. With this pressure the addition of the condenser greatly increased the power obtained from a given size of cylinder and quantity of steam. But at the present time no one would think of using

less than 80 lbs. pressure in an electric-lighting plant, and for large central stations 125 to 150 lbs. is common; consequently, the additional effective pressure gained by condensation is a very small percentage of the boiler pressure, but it adds materially to the power and efficiency, as explained in Chapter XII.

There are two radically different types of condenser, — the jet and the surface condenser.

The jet condenser is the original form, having been employed by Watt, and consists of a chamber into which the exhaust steam and a jet of cool water are conveyed, the former being condensed by actually mixing with the latter. The volume of the chamber is ordinarily from one-third to one-half that of the cylinder of the engine.

Forms of jet condenser are made by the manufacturers of steam-pumps, such as the Blake, Worthington, Knowles, and others. The Blake vertical type, shown in Fig. 38, consists of a condensing-chamber, combined with steam-cylinders which operate the two pumps, — one to deliver the jet of water to the chamber, and the other to remove the air from it. The jet condenser is used where the condensed water is not returned to the boiler, as the steam takes up oil in the cylinder which may be objectionable in the boiler (see page 113). This type is also used with salt or very impure condensing-water (in land practice), because it is more easily cleaned than the surface type. A condenser operated by its own steam-cylinder is called *independent*, and is generally preferable to those in which the pumps are connected to and worked by the moving parts of the engine, because the condenser may be started up before the engine, or separately controlled in any way that may be desired.

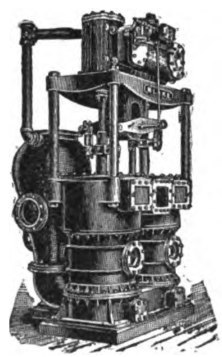
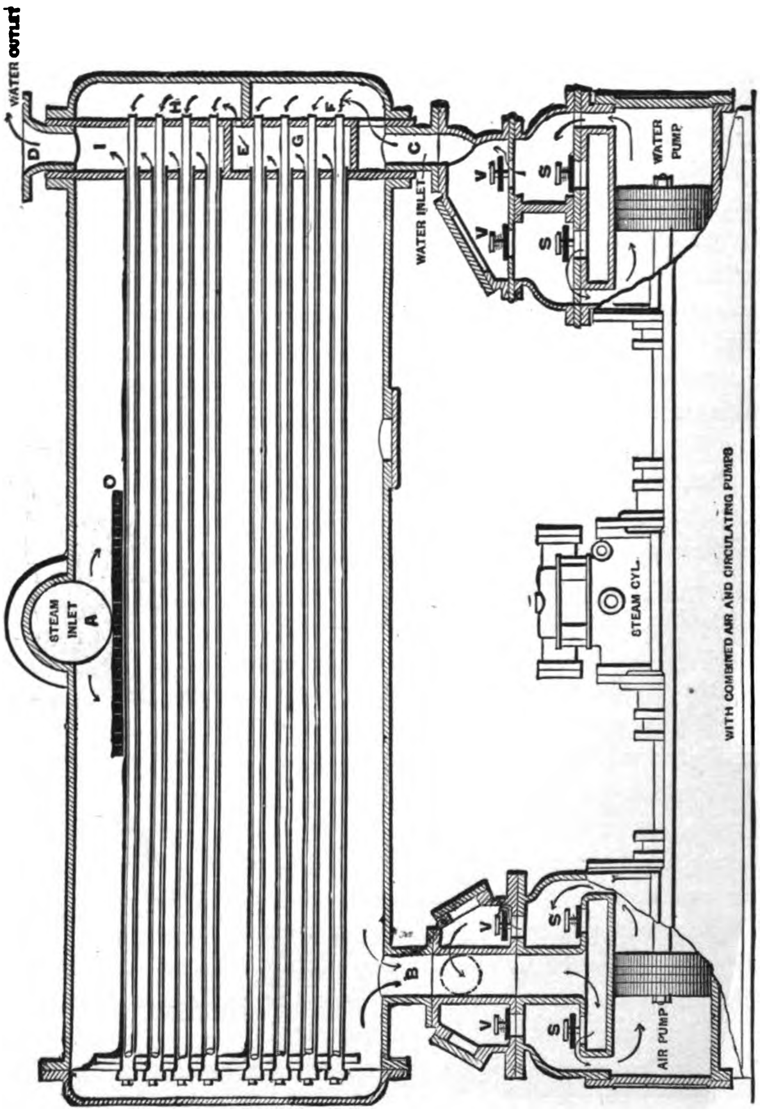


Fig. 38.
Blake Jet Condenser.

The surface-condenser differs from the foregoing in the fact that the exhaust-steam is not mixed nor brought in actual contact with the water which condenses it. In the surface-condenser the steam is separated from the cool water by metallic partitions or tubes, the ordinary arrangement being to pass the cool water through brass tubes around which the steam is caused to circu-

late, or *vice versa*. The condensing-surface required is usually from 1½ to 3 square feet per indicated horse-power.

The Wheeler condenser is a standard form of surface-con-



WITH COMBINED AIR AND CIRCULATING PUMPS

Fig. 39. Section of the Wheeler Surface Condenser.

denser. Fig. 39 represents a section of this apparatus in which the exhaust-steam from the engine enters the condenser by the nozzle *A*, and comes in contact with the perforated scattering-

plate *O*, which protects the tubes from the direct impingement of the steam. The condensed steam gravitates to the bottom of the condenser, and flows through the outlet *B* to the air-pump, which discharges it through a pipe represented by a dotted circle in the figure. The circulating-pump on the right forces the cooling water through the inlet *C* into the compartment *F*, from which it passes into the small tubes as indicated. After traversing the small tubes, the water returns through the annular spaces between these tubes and the large tubes which surround them, and empties into the compartment *G*; thence it flows through the passage *E* into the compartment *H*. The water then circulates in a similar manner through the tubes of the upper section, and finally discharges through the outlet *D*. Both the air-pump and circulating-pump are operated by a single direct-acting steam-cylinder, as shown. The tubes are arranged to be easily unscrewed and removed for cleaning or repairs.

Water for Condensation. — The obtaining of a sufficient supply of water for this purpose is often a difficult matter, and should be considered in locating the station, as stated in Chapter V. The quantity of condensing-water required depends upon its temperature, but it is ordinarily estimated to be from 30 to 50 times the weight of water evaporated in the boiler; hence it takes about 500 to 1,000 pounds per horse-power for each hour that the engine is working. This amount being so very large it is evident that condensing-engines cannot be used unless an almost unlimited supply is available, such as that afforded by a river or other large natural body of water. The waterworks of a city, for example, could not be expected to furnish condensing-water, no matter how ample the supply might be, and in any case the water-tax would be prohibitive. It is possible to use water for condensing which is far less pure than that required in the boiler, deposition of impurities being much less objectionable, so that salt water is often employed for the condensers of electric-light stations where these are located on the seashore or on an arm of the sea. It is, nevertheless, very undesirable even for condensing-water to contain salts or dirt, since they clog and interfere with the working of the condenser and pumps. For this reason condensing-engines are not used in some cases where an abundant but impure supply of water is at hand; and in other instances a large well is

dug to obtain the condensing-water, even when the station is close to the shore.

The station of the Internationale Elektricitäts Gesellschaft of Vienna, situated on the Danube, takes water for condensation from a well to avoid the dirt of the river-water.

If the natural supply of water is insufficient, cooling towers enable a small amount to be used over and over again. In these the water is cooled by evaporation and exposure to currents of air in a number of large, shallow pans over which it flows successively or in checker-work through which it trickles, the object being to obtain large cooling surface.

Principles of Compound Engines. — In the compound engine the steam partially expands in one cylinder, and then passes to another cylinder, in which it completes its expansion. At first sight it is difficult to see any advantage in thus subdividing the expansion and work of the steam, since the efficiency and total capacity of a steam-engine to do work depend upon the initial and final temperatures of the steam, and would seem to be entirely independent of whether the expansion all takes place in one cylinder or not. As a matter of fact, this would be true if the walls of the cylinder did not take up and give out heat to the steam at different parts of the stroke, causing serious losses and modifications in the action of the steam in the cylinder.

For example, let us assume that the steam enters the cylinder at a pressure of 100 lbs. above that of the atmosphere, which corresponds to a temperature of 170° C., and that it leaves the cylinder at the atmospheric pressure which corresponds to 100° C. Thus the change in the temperature of the steam during each stroke is 70°, and if the internal surface of the cylinder is cooled down to 110° by the heat taken from it by the exhaust-steam, then the incoming steam at the next stroke will find the cylinder to be 60° below its own temperature, and it will therefore give up a great deal of its heat to the cylinder by radiation as well as by actual contact. Steam, unfortunately, has considerable power either to give out or to absorb heat, and results show that the losses in the cylinder from this cause are very serious. It might be thought that the heat returned to the steam by the cylinder during the latter part of the stroke would counterbalance the loss in the beginning; but most of the heat given

back to the steam passes away in the exhaust, since the latter is in contact with the cylinder during the entire back stroke.

The reason for the loss may also be understood if we consider that the effect of this giving and taking of heat is to reduce the initial temperature and increase the final temperature of the steam, and the efficiency is directly dependent upon the difference between these two temperatures. (Page 91.)

The trouble is further aggravated by the fact that the steam is usually "wet;" i.e., is slightly condensed when it enters the cylinder, and becomes still more so by the act of expansion, even though it did not give up any of its heat to the cylinder. Hence the aggregate effect due to all these causes produces a very considerable condensation and diminution of pressure, and is one of the chief sources of trouble and loss in the action of the steam-engine. The most evident way to mitigate this difficulty would be to *superheat* the steam; that is, raise its temperature above the saturation point after it has left the boiler, so that it is capable of losing heat in the cylinder and still remain uncondensed. This plan has been continually advocated from the time of Watt to the present day; but, as a matter of fact, it is rarely adopted, owing to the complication and practical difficulties which it involves. Its advantages are so great, however, that it would seem as if it ought to be developed and accepted generally. The method of superheating steam by introducing hot air at 553° F. into the cylinder and jacket has been tried by Professor Andrew Jamieson, who obtained good results.*

Another way to diminish the cylinder losses is to adopt high speed, and thus reduce the time during which the steam can transfer its heat to the cylinder. It is generally stated by authorities that cylinder condensation varies approximately as the square root of the time of action,† other things being equal. This is one of the advantages of the many types of high-speed engines now employed in electric lighting. But the most successful method of reducing cylinder losses is that of multiple expansion as obtained in compound or triple expansion engines. To appreciate the advantage of this method let us take the same case as before — an initial pressure of 100 lbs., and a final pressure of

* *Electrical World*, July 20, 1895.

† Thurston's *Manual of the Steam-Engine*, Part II., page 702.

that of the atmosphere, but assume that the steam expands from 100 lbs. pressure down to 40 lbs. in one cylinder, and then passes to another cylinder, in which it completes its expansion. The initial temperature is 170° C., as before, but it only falls to 141.5° (which corresponds to 40 lbs. pressure) in the first cylinder, in which the total range is therefore only 28.5°, and the incoming steam is only 18.5° above the temperature of the surface of the cylinder, assuming, as before, the later to be 10° above the steam which leaves it. Similarly in the second cylinder the total range is 41.5°, and the cylinder would be 31.5° cooler than the steam which enters it.

Thus it appears that the maximum and average differences in temperature between the steam and the cylinder walls in the compound engine would be less than half as great as those in the single cylinder. A triple-expansion engine in which the steam is successively expanded in three cylinders would have about one-third the range of temperature in each cylinder that would occur in a simple engine having the same initial and final pressures, and the losses would be still further reduced. To offset the advantage obtained by dividing the expansion between two or more cylinders, there is the fact that the total internal surface of the two cylinders of a compound engine would be greater than that of a single cylinder, and the time during which the steam can transfer its heat to the cylinder is also greater, other things being equal.

But the results of general experience and actual tests show a decided economy secured by the use of compound engines in place of simple engines; and triple and quadruple expansion engines show a still further saving in fuel consumption, provided the size and importance of the plant warrant the increased cost, complication, and care which multiple expansion involves. But it should be remembered that a great deal of the higher efficiency often credited to compound and triple expansion engines is due to the *increased steam-pressure* which is applied to them.* This in itself gives higher economy even in a simple engine; and while it is decidedly preferable to adopt multiple expansion with high steam-pressures, nevertheless high pressure can be used, and will increase the efficiency even in a simple engine. For example, a locomotive requires less coal at 175 lbs. pressure than it

* See page 77.

does at 150 lbs. to give the same power, even though it is a simple, and not a compound, engine.

Besides the economy of the compound engine in reducing cylinder condensation, it also has advantages in distributing the strains and work of the engine between two cylinders instead of one; and if the cranks operated by the two cylinders are set at right angles to one another, then the rotational effect is more uniform, and the engine will not catch on the dead center in starting.

The only essential advantage, however, of compound engines is the reduction of the range of temperature in any one cylinder; and if some practical means were devised to prevent the cylinder from absorbing heat from the steam, it is very doubtful if compound engines would be used to any great extent.

For example, it has been attempted to line the cylinder with bismuth, lead, or some alloy which is a poor conductor of heat and also has a low specific heat; but these materials are not sufficiently strong or durable for the purpose. Dr. Charles E. Emery lined the whole interior of the cylinder with glass or porcelain, but without permanent success.* The use of plenty of oil in the cylinder, or coating the interior with varnish, both tend to reduce cylinder condensation.† This matter has also been investigated by Mr. Croll.‡ It is certainly to be hoped that some such method to reduce cylinder condensation may be made practicable.

The subject of condensing and multiple-expansion engines, particularly the effect upon them of variable loads, is discussed in Chapter XII.

The typical forms of compound and triple expansion engines used in actual practice are described in the following chapter.

* *Trans. Am. Soc. Mech. Engs.*, 1881.

† Thurston's *Manual of the Steam-Engine*, Part II., page 704.

‡ *London Electrical Review*, Oct. 4, 1895, p. 416.

CHAPTER XI.

TYPICAL FORMS OF STEAM-ENGINE FOR ELECTRIC LIGHTING.

HAVING considered the general principles and construction of steam-engines, let us now examine the most important types used in electric lighting. These may be grouped in four general classes: —

1. Large, *low-speed* engines of the Corliss or similar type, usually running at 50 to 125 revolutions per minute.

2. Small and medium-sized *high-speed* engines running at 200 to 400 revolutions per minute.

3. A sort of compromise between the two foregoing, which has been developed for direct coupling with dynamos. These are usually vertical and compound or triple expansion, being of the so-called "marine type." If these are large, they approximate class 1; if they are small, they resemble class 2. Their speed is usually between 125 and 200 revolutions per minute.

4. Steam turbines usually running at very high speeds of one or even several thousand revolutions per minute.

Besides the above prominent classes, peculiar forms of steam-engine, such as oscillating and rotary types, have been tried or proposed; but they have not been used to a sufficient extent to warrant much attention being given to them.

Corliss Engines. — The most successfully and extensively used stationary engines are of the type devised by George W. Corliss of Providence, R.I., in 1849. The principal features of this engine are the subdividing of the valve functions and the automatic cut-off, by which the admission of steam to the cylinder is controlled by the governor, so that the point of cut-off varies in proportion to the load. Many modified forms and improvements in detail have been brought out; but the Corliss valve-gear remains substantially the same in its general construction and action. At first sight it might appear to be a complicated and somewhat clumsy mechanism; but its long-continued and almost

universal success; and the fact that there is a tendency to revert to it, rather than to depart from it, are conclusive proofs of its great merit. Its great advantages are good regulation, correct steam distribution and small clearance space.

A standard form of Corliss engine is shown in Fig. 40; typical Corliss valve-gear in Fig. 41; a form of releasing mechanism in Fig. 41*a*; and a special form of valve-gear in Fig. 42. In

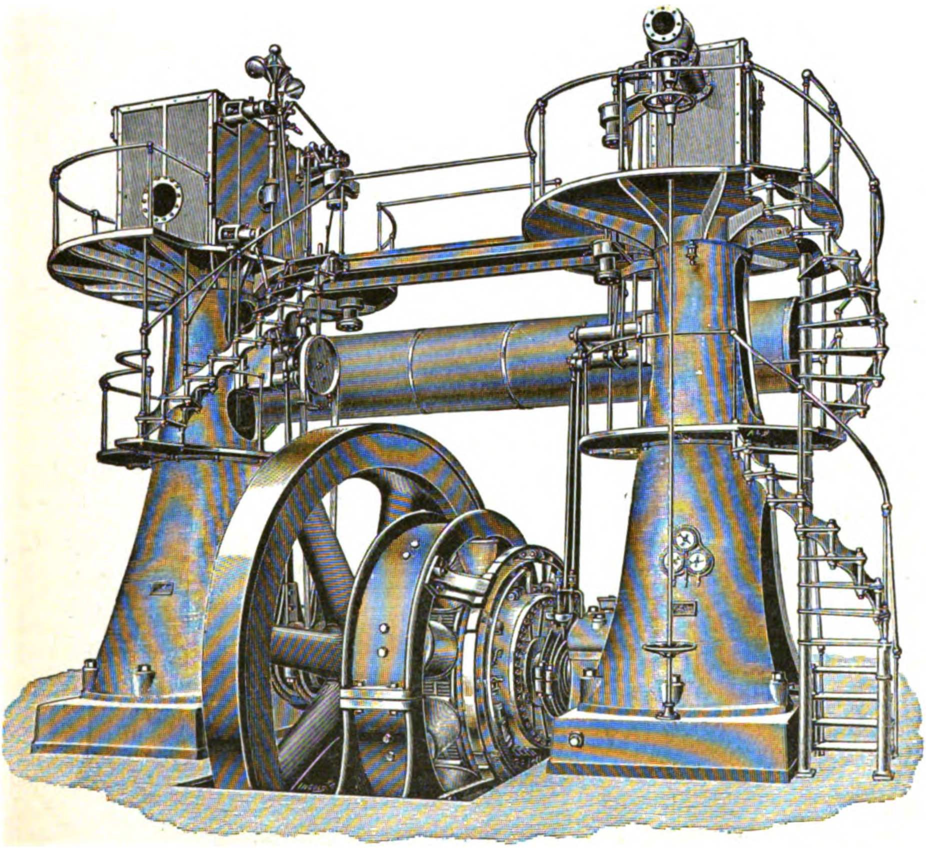


Fig. 40. Reynolds-Corliss Vertical, Cross-compound Engine.

Corliss engines each cylinder has an admission valve, *V* (Fig. 41), and an exhaust-valve, *E*, at each end. They are all of the rotary type, either single-ported (*J*) or double-ported (*K*), the object of the latter being to obtain a double opening with the same angular motion. The exhaust-valves *EE* are usually placed below to allow any water to flow out readily. All four

valves are connected to the wrist-plate *W* by adjustable rods *LLLL*. This wrist-plate is pivoted on the cylinder *DD*, and is caused to oscillate through a constant angle by a rod, *R*, connecting with an eccentric on the main shaft. The exhaust

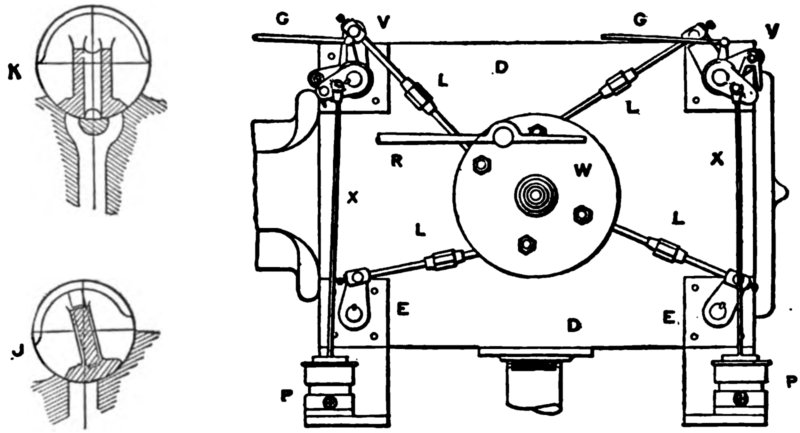


Fig. 41. Details of Corliss Valve-gear

valves *EE* are opened and closed positively, while the admission valves *VV* are opened by a grab-hook which releases at a certain point in the stroke, allowing the valve to close by gravity, accelerated by vacuum pots *P*, springs or steam pressure, in order to secure a rapid cut-off. There are innumerable forms of releasing gear, the general principle being about the same. A simple type in Fig. 41*a*, used by Fraser and Chalmers, consists of a bell-crank lever, *AA*, which carries a pivoted hook, *H*, forced inward by a spring, as shown. This lever, being connected to the wrist-plate by the rod *L*, rocks back and forth. The hook *H* in its lowest position engages with the drop-lever *B*, and as the bell-crank lever *AA* moves upward, as indicated by the arrow,

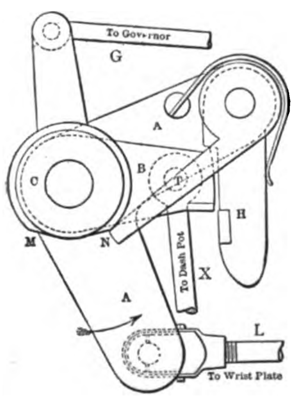


Fig. 41a. Corliss Releasing Gear

the lever *B* is carried around to the position shown, and being connected to the valve, causes it to open. At that point the trip-lever *T* comes in contact with the projection *N* on the cam *C*, which forces it and the hook *H*, to which it is attached, outward, thus re-

leasing the drop-lever B, which rapidly falls to its original position by the action of the dash-pot. The cam C is connected to the governor so that the position of the projection N is always such that the cut-off will occur at the proper point to maintain constant speed. Safety is secured by the projection M on the knock-off cam C, which in the lowest position of the governor comes in contact with the trip-lever T, preventing the hook H from engaging. Hence the valve is not opened at all, and the engine stops in case the governor belt fails. As already stated, there are very

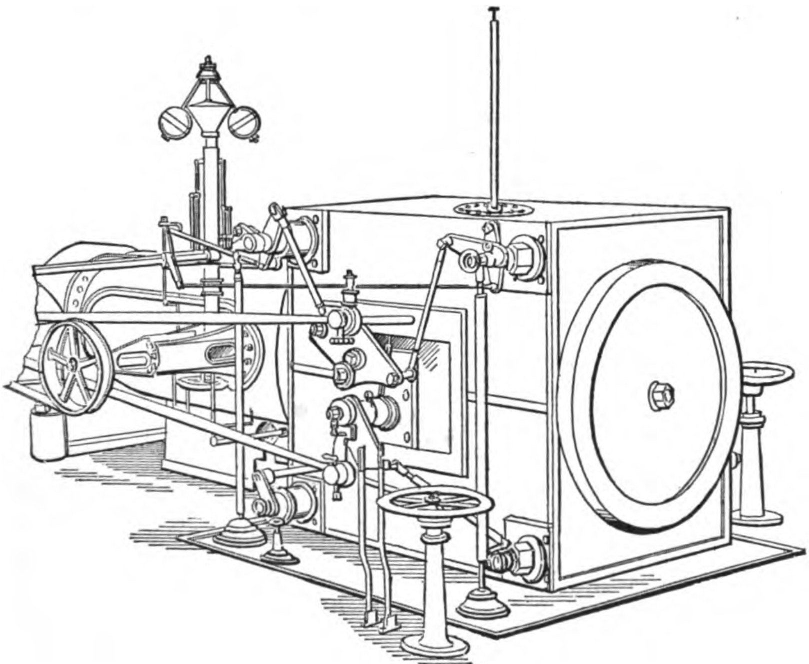


Fig. 42. Corliss Valve-gear with Double Wrist-plate.

many other forms of Corliss valve-gear. They are all limited in speed to about 100 or 125 revolutions per minute, although sometimes run up to 150 revolutions per minute. This limitation applies to almost any form of releasing valve-gear, because the cut-off is not rapid enough for high speeds. For that reason some type of cut-off with *positive* action or the simple throttle governor is adopted for high-speed engines, being described later in the present chapter.

On the other hand, the practicable speed of Corliss engines may

be increased by accelerating the cut-off. The ordinary dash-pots (*P* in Fig. 41) act also as vacuum pots, that is, a partial vacuum is formed when the valve is opened and the rod *X* is lifted. When the valve is released and closed rapidly by the atmospheric pressure, the small amount of air in the dash-pot is compressed and acts as a cushion to arrest the rapid motion. In some cases the motion is accelerated by springs or by steam pressure. In the Harrisburg type of Corliss engine a small auxiliary cylinder receiving steam from the main cylinder steam-chest acts to produce a rapid closing of the valve. A compound engine of this kind having cylinders of 17 and 32 inches diameter with 26-inch stroke develops 450 indicated H.P. at 125 lbs. pressure and 160 revolutions per minute, which is nearly twice the speed of ordinary Corliss engines of corresponding power. The governor is of the inertia type similar to those used on high-speed engines (Fig. 43), the necessary speed being obtained by belting from the main shaft. The larger Ball and Wood engines are provided with Corliss valves, but the cut-off is made to occur positively by the direct action of an inertia governor. The latter is mounted on the main shaft, since the speed is relatively higher, being 130 to 150 revolutions per minute for the 1200 H.P size and 180 to 200 for the 300 H.P. cross-compound vertical engine. These engines and the Harrisburg Corliss type mentioned above are particularly designed for driving generators directly, being classed with the medium-speed engines described later in the present chapter.

Another limitation of the Corliss valve-gear is the fact that the cut-off is restricted with a single eccentric and wrist-plate, as in Fig. 41. If the admission and exhaust valves are actuated by one wrist-plate, a very late cut-off is likely to delay the closing of the exhaust, so that both valves are open simultaneously at the same end of the cylinder at a certain part of the stroke. Special forms of gear have been devised to overcome this difficulty and give a range of cut-off to eight-tenths stroke with a single eccentric. Ordinarily this result is secured by providing two wrist-plates, each operated by its own eccentric, as in Fig. 42. Thus the action of the admission and exhaust valves is independent and the range of cut-off made as great as desired. When arranged in this way they are often called "heavy-duty engines," because they have considerable overload capacity. For steady work it is not

usually economical to have the cut-off later than one-fifth or one-quarter stroke. In many cases, however, the service is such that overloads occur only for short periods of time, so that it is more convenient and probably more economical to allow temporary overloading with late cut-off rather than install and operate extra engines. The same is true of electric generators which are guaranteed to carry 25 per cent overload for two hours.

The forms of Corliss engine commonly built are the simple, tandem-compound and cross-compound, both horizontal and vertical, the first of these being represented in Figs. 41 and 42 and the vertical cross-compound in Fig. 40. This last type is very popular in the larger electric-light and power stations, being economical in floor space; in fact it may be taken as standard practice for reciprocating steam-engines. There are two other modifications of this general form, one having the fly-wheel and generator mounted at one end outside of the housings and the other has two generators outside, one at each end, the latter being used to supply a three-wire system directly.

High-speed Engines.—*The automatic cut-off high-speed type* of engine is especially interesting and important in connection with electric lighting; in fact the development and extensive use of these engines are largely due to their application to this purpose. The distinguishing feature of this type consists in placing the governor upon the main shaft or fly-wheel and connecting it directly with the eccentric, so as to control its action and vary the point of cut-off. This location of the governor is made possible by the fact that these engines are of sufficiently high speed to give the required centrifugal force and insure its proper action; whereas the governor of a low-speed engine is mounted on an independent spindle at some distance from the main shaft, and connected to it by belting or gearing, to obtain the necessary speed of rotation.

In Corliss and other detachable or "drop" cut-off engines, also in cam-motion valve-gear, the speed is limited by the fact that the cut-off is not rapid enough with respect to it, hence some *positive* cut-off is required in high-speed engines. This usually consists in directly connecting the cut-off device with the eccentric, so that the former is forced to operate. The direct connection between the governor and valve-gear is a great ad-

vantage of the high-speed type in many ways, and secures compactness as well as quickness and effectiveness of regulation. High-speed engines are not usually of such high economy as the Corliss, for example ; and the wear and tear, attendance and lubrication are greater. They are, however, and probably will continue to be, commonly employed for smaller installations, whether isolated plants or central stations. Compactness, close regulation, convenience of driving by direct connection or by belting, and avoidance of flickering in the lamps, with moderate diameter and weight of fly-wheel, are all distinct and important advantages that these engines possess, and which make them in many cases the most desirable form to select. There are so many excellent forms of high-speed engines in the market that it is impossible to describe all of them ; but certain common and standard types are here given as examples.

The Armington & Sims Engine has been employed for driving dynamos in central stations and isolated plants from the first installations up to the present time. For many years it was the standard engine adopted in nearly all the Edison as well as other stations and plants. Since that time many other high-speed types have been introduced for the smaller plants; and for central stations as well as many isolated plants, Corliss or other low-speed engines, steam-turbines or gas-engines are used. A common form of this and other makes of high-speed engine is shown in Fig. 43. It is provided with two pulleys, one on each side, and is therefore constructed with a "center crank" working between "double disks." This arrangement has been used when two dynamos were driven from one engine by belting for supplying a three-wire system or series direct-current arc lamps as illustrated on page 50. It is often employed for direct connection with dynamos, the armature being mounted in place of one of the pulleys. A disadvantage of this design is the fact that the crank and connecting-rod end are inaccessible in the narrow space between the two disks, and therefore somewhat difficult to adjust or repair. For cases where only a single pulley is required, the single-disk type of engine is made by this as well as by other manufacturers. The same form is also employed for direct connection, the shaft being extended so that the armature may be mounted alongside of the fly-wheel, as represented in Fig. 74.

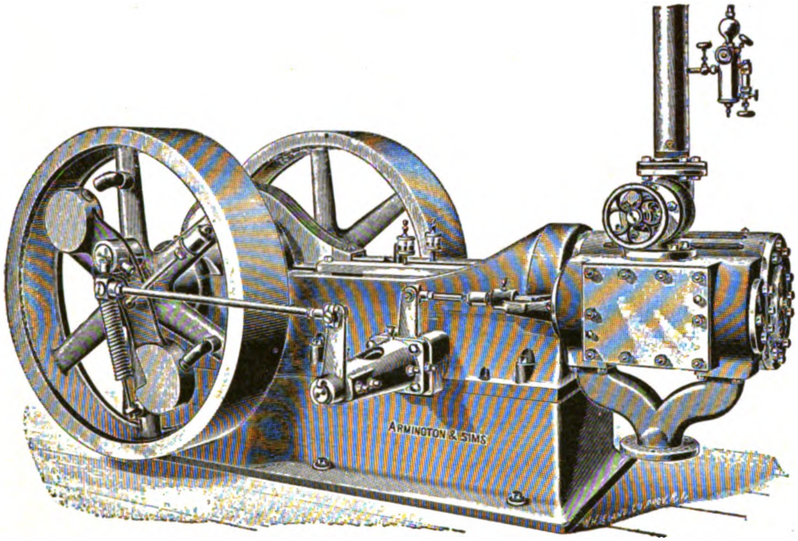


Fig. 43. The Armington & Sims Simple Horizontal High-speed Engine.

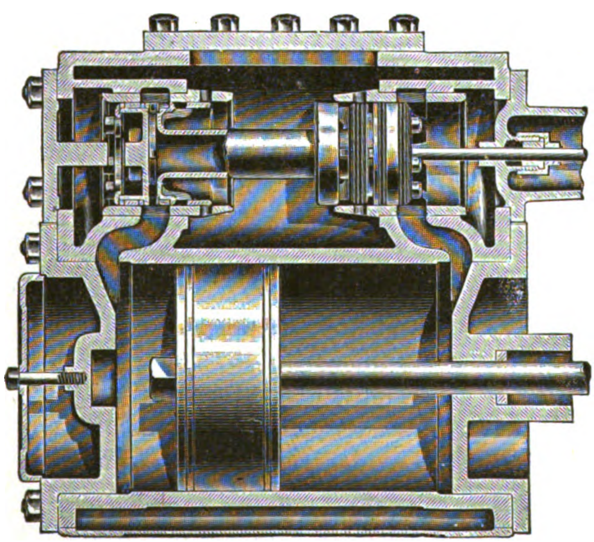


Fig. 44. The Cylinder and Value of Armington & Sims Engine.

The forms of valve and governor used in the Armington & Sims engine are its chief characteristics. A section of the cylinder and valve is shown in Fig. 44. The valve is of the piston type, and is made hollow, so that the steam enters the cylinder by two paths from the steam-chest, which facilitates the taking of steam promptly at the beginning of the stroke. For the same reason the cut-off is more sudden and definite. The illustration shows that the steam pressure, being exerted equally in all directions, is balanced, an advantage of piston or cylindrical slide-valves already stated on page 129. The piston is provided with self-adjusting packing-rings in order to maintain a steam-tight contact with the valve-seat, which consists of a hard cast-iron bushing.

This and practically all other high-speed engines are provided with the shaft governor (page 134), usually mounted upon the spokes of the fly-wheel. These governors consist essentially of one or two pivoted weights which act by centrifugal force, balanced by springs, to shift the eccentric so as to vary the cut-off. In the latest forms the *inertia* of the weights is also utilized to secure more nearly perfect regulation. Formerly centrifugal force alone was relied upon, and inertia had a good or a bad effect, according to the way the parts happened to be arranged. The Rites type of "inertia governor" is employed on the latest Armington & Sims engines. It consists of an arm with weights at each end, pivoted near its center upon a stud fixed to a spoke of the fly-wheel or to a special governor-wheel mounted upon the the shaft as illustrated in Fig. 43. A spiral spring is attached at one end to a spoke of the wheel and at the other to the weighted arm. Similar types are shown in more detail in Figs. 50 and 51. The valve-rod is connected to an eccentric wrist-pin carried by the weighted arm. Considering the effect of centrifugal force alone, it is evident that the higher the speed the greater will be the tendency for the weighted arm to turn clockwise and stretch the spiral spring. The weights at the ends of the arm are hollow, so that a greater or less quantity of lead may be introduced and the spring tension is also adjustable, hence it is possible to balance the two forces for normal speed. Furthermore they are balanced for all positions of the arm, as explained on page 137. Any increase in speed tends to cause the upper weight to swing

to the right and come in contact with the stop shown, and any decrease in speed will cause the lower weight to move towards its stop. In the former case the eccentric pin is shifted nearer the center of the main shaft so that the throw of the valve is reduced and the cut-off occurs earlier in the stroke, thus tending to bring the speed down to normal. If now the effect of inertia is also considered, it is evident that a sudden acceleration of speed will tend to cause the weighted arm to lag behind the fly-wheel.

Since the direction of rotation is counter-clockwise, the lagging of the arm is in a clockwise direction. Hence inertia produces the same effect as centrifugal force with acceleration of speed. There is this difference, however, that inertia acts more promptly, with sudden changes, whereas centrifugal force does not act until after the change has occurred. It should be noted, on the other hand, that gradual variations in speed would have practically no effect upon the governor due to inertia, while centrifugal force would have its full influence. A governor acting by inertia alone would therefore allow the speed to rise or fall gradually to any extent. In order to prevent the action of the governor from being too sudden a dash-pot is connected to the weighted arm, as shown in Fig. 43. These engines are built in the simple form (Fig. 43) in 18 sizes, from about 30 to 500 H.P., the speeds being respectively 275 to 350 and 175 to 225 r.p.m.; also 16 sizes of tandem-compound engines from about 100 to 500 H.P., with speeds of 225–300 and 175–225 r.p.m.; also 18 sizes of cross-compound horizontal or vertical engines from about 100 to 700 H.P., with speeds of 225–300 and 175–225 r.p.m.

The Ball Engine, another well-known high-speed type, manufactured at Erie, Pa., is called the Erie Ball Engine, to distinguish it from two others of similar name described later. The characteristic feature of all three forms is the valve, consisting of two parts connected by a telescopic joint; this works as a double-faced slide-valve between two surfaces in which the ports are formed, as represented in Fig. 45. The steam which is admitted to the inside of the valve through the top presses the two faces apart with respect to each other and against the ports above and below. The object of this arrangement is to insure a steam-tight contact and at the same time to allow for wear.

The new governor applied to this engine is of the inertia type, somewhat similar to that illustrated in Fig. 43. The chief differences are the fact that a flat-leaf spring is used instead of a coil spring, the weight being mounted directly upon the end of the spring, and the valve-rod is actuated by an eccentric in place of a wrist-pin.

These engines are made in the simple form in 22 sizes, from about 30 to 300 H.P., with normal speeds of 325 and 200 r.p.m.

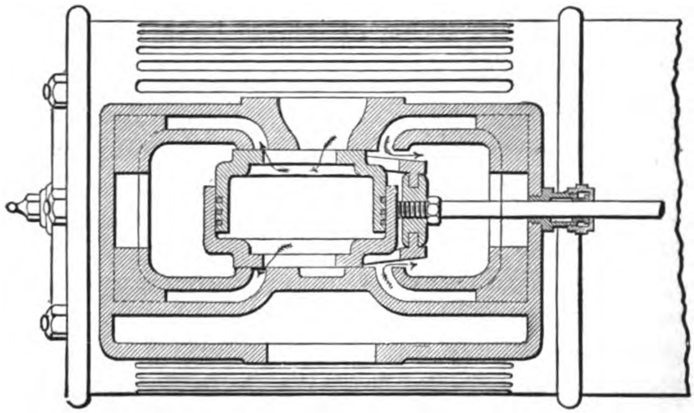


Fig. 45. Section through Valve of Ball Engine.

respectively; also 22 sizes of condensing and non-condensing tandem-compound engines from about 70 to 350 H.P., with normal speeds from 280 to 200 r.p.m.; also 26 sizes of cross-compound condensing and non-condensing engines, from about 130 to 400 H.P., with normal speeds from 280 to 200 r.p.m.

The American Ball Engine of the high-speed type employs a valve closely similar to that illustrated in Fig. 46. The governor is of the inertia type similar to that represented in Figs. 43 and 51. It is so designed that the throw of the valve and angular advance of the eccentric-pin with respect to the main crank are varied so as to keep the lead and compression nearly constant for all loads. These engines are made simple, cross-compound, and tandem-compound of the horizontal form of the usual sizes. Another arrangement of this engine that is peculiar is the duplex-compound type represented in Fig. 46. The high-pressure cylinder is placed directly under the low-pressure cylinder instead

of on one side as in the cross-compound, or end-to-end as in the tandem-compound designs. It possesses the advantages that the floor space occupied is no greater than for a simple engine.

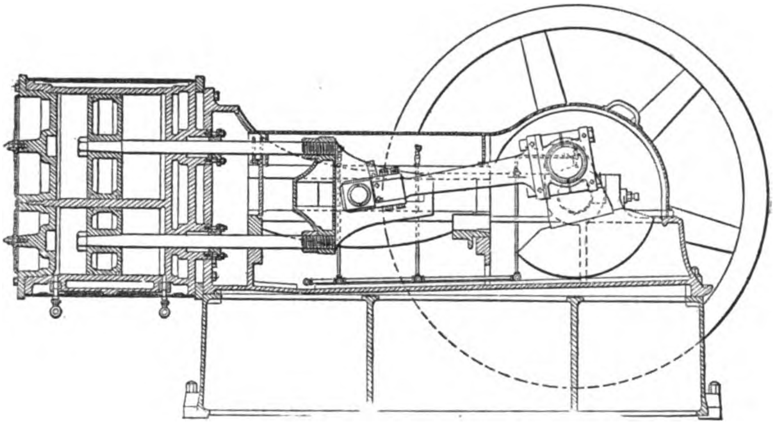


Fig. 46. Cross-Section, American Ball Duplex-Compound Engine.

This design is built in nine sizes from 60 to 500 H.P., the speeds being respectively 325 and 180 r.p.m.

The Ball & Wood High-speed Engines are provided with valves similar to those already described (Fig. 45), except that for the low-pressure cylinder of the horizontal compound form a rotary

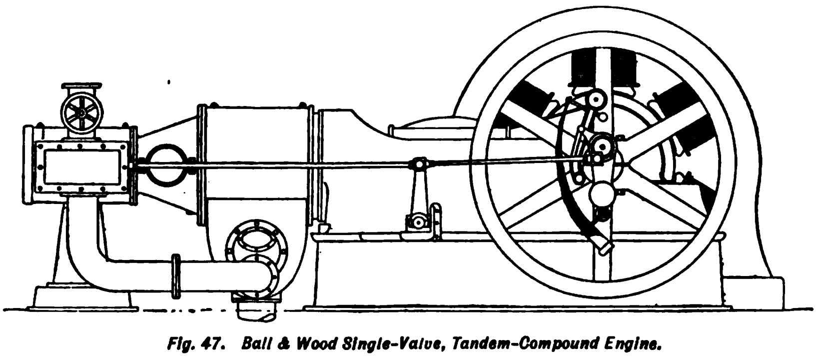


Fig. 47. Ball & Wood Single-Valve, Tandem-Compound Engine.

valve is employed. The valve-chest in this case is cylindrical being placed transversely to the axis of the cylinder and directly below it. The governor is of the inertia-centrifugal type similar to those illustrated in Figs. 43 and 51. Its general construction may be seen in Fig. 47. The upper weight is thrown outward by centrifugal force as well as by inertia with acceleration of

speed, these forces being balanced by the curved leaf spring acting through a pin as shown. The lower mass is influenced only by inertia and supplements the effect of the other weight. The two are connected to the eccentric so as to shift it and vary the cut-off. The simple, horizontal form for belt or direct connection is made in twenty sizes from 40 to 375 H.P., running at 290 to 325 and 180 to 200 r.p.m., the piston speeds being 467 and 600 feet per minute respectively. The sizes of the tandem-compound type represented in Fig. 47 for direct connection are given in the following table:

BALL & WOOD TANDEM-COMPOUND ENGINES (SINGLE VALVES).

HORIZONTAL DIRECT-CONNECTED TYPE.

Engine.			Generator. K. W.	Rev. per Minute.	Approximate Floor Space.		Wheels.		Diam. Steam Pipe. Inches.	Diam. Exhaust Pipe. Inches.	Approx. Wgt. with Base. Pounds.
No.	H.P.	Stroke. Inches.			Width.	Length.	Diam. Inches.	Face. Inches.			
32	80	*11	50	275–310	8′ 3″	12′ 9″ 12′ 9″	54 60	13	3½	5	13200
34	115	12	75	265–290	9′ 9″	13′ 10″ 13′ 10″ 13′ 10″	54 60 66	13	4	6	16800
35	150	14	100	250–275	10′ 10″	15′ 5″ 15′ 5″ 15′ 5″	68 72 78	15½	4½	7	22500
36	175	16	125	225–250	11′ 4″	16′ 6″ 16′ 6″ 16′ 6″	72 78 84	17	5	7	25000
38	225	*16	150	215–235	12′ 4″	17′ 0″ 17′ 0″ 17′ 0″	72 78 84	19	6	8	31000
40	300	18	200	190–210	13′ 9″	19′ 8″ 19′ 8″	84 90	21	6	9	49000
42	375	18	250	180–200	14′ 0″	20′ 4″ 20′ 4″	84 90	22	6	10	51000

The option is reserved to proportion the cylinders of compound engines to suit varying conditions.

* The engines indicated by asterisk are specially designed for the powers given, and are heavier and larger than those of same stroke of smaller powers.

The above table is based on the report of the Standardization Committee of the Amer. Soc. Mechan. Eng.

Horizontal, cross-compound (single-valve) engines are also manufactured in nine sizes, from 150 to 600 H.P. and speeds of

275 to 310 and 180 to 200 r.p.m. respectively. Horizontal tandem- and vertical cross-compound engines of greater power are equipped with Corliss valves and belong to the medium-speed class described later, as already stated on page 160.

The McIntosh and Seymour High-speed Engine employs one form of governor for single-valve and another for double-valve construction. Both are of the shaft type and similar, but differ from that shown in Fig. 43 and others already described in the fact that the weights are not arranged to act by their inertia, centrifugal force alone being relied upon.

The valve is of the piston form, somewhat similar to that represented in Fig. 44, but it works in a valve-seat which is split, and can be contracted by the adjusting-screw shown in Fig. 48. This split ring, which forms the valve-seat, is made tapering towards the ends, so that it tends to preserve a perfect circle even when contracted. This enables the fit of the valve to be perfectly adjusted at any time in order to take up the wear and avoid leakage.

The ordinary horizontal single-cylinder form of this engine is made in twenty sizes, from 22 to 500 H.P., with speeds from 320 to 175 r.p.m. respectively. Numerous sizes of tandem-compound high-speed engines are also built, ranging from 65 to 500 H.P. and from 275 to 175 r.p.m.

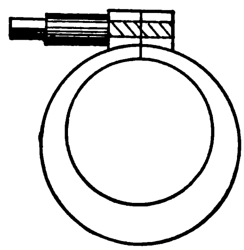


Fig. 48. Adjustable Valve-seat.

Larger engines of from 300 to 3000 H.P., both vertcal and horizontal, are made, but these belong to the medium-speed class and will be described later.

The "Ideal" Engine, manufactured at Springfield, Ill., belongs to the class in which the working parts are completely inclosed in a cast-iron case. Its construction is very similar to that of the "Harrisburg Idéal" engine represented in Fig. 49. This arrangement makes the engine self-lubricating, because the supply of oil which is kept in the bottom of the case is thrown about by the motion of the crank-pin, thereby drenching the working-parts with lubricant as represented. Special channels are also provided to catch the oil and convey it to points which it would not reach directly. For example, there is one at the extreme end of the

casing; this supplies the main bearings with a constant flow of oil. The governor is of the Rites inertia-centrifugal type similar to that shown in Fig. 43, but an eccentric is used instead of a wrist-pin. Either of two styles of valve may be used, both being

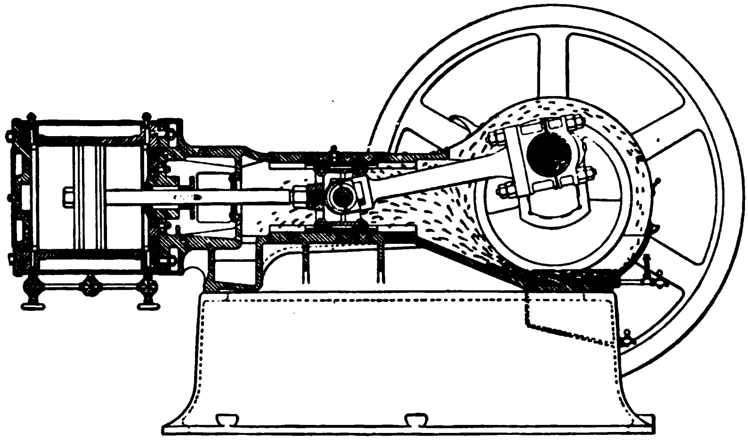


Fig. 49. Fleming Center Crank Engine.

of the piston form. One is simply a hollow casting working in a valve-seat consisting of cast-iron bushings. If the wear becomes sufficient to allow leakage a new valve slightly larger than the

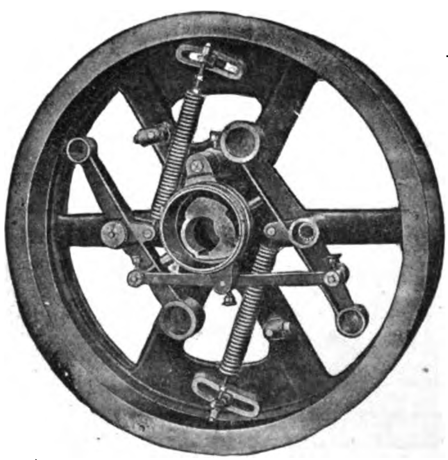


Fig. 50. Fly-Wheel and Governor of Harrisburg Engine.

original is furnished by the manufacturer, also a boring-bar and reamer. With the two latter the bushings are bored out to fit the new valve. The other kind of valve is adjustable, being pro-

vided with split rings that may be expanded by means of a wrench. These engines with single cylinders are built in twenty-two sizes, from 10 to 400 H.P., the speeds being respectively 400 to 500 and 180 to 200 r.p.m. Tandem-compound engines of similar design are also made.

The Harrisburg Ideal and Standard Engines are similar to the foregoing, as already stated, being shown in Figs. 49 and 74. The most prominent difference is in the governor, represented in Fig. 50. It is of the inertia-centrifugal type, but comprises two weighted arms instead of the single bar of the Rites construction. The weights are thrown outward by centrifugal force with increase of speed, and being connected to the eccentric, as illustrated, the latter is shifted so as to cut off the steam earlier in the stroke. When a load of 125 per cent of the rated power is suddenly applied to one of these engines, it is guaranteed not to vary in speed more than 1½ per cent, and if this load is instantly thrown off the variation is not greater than 1 per cent. The following table gives data concerning the "Standard" type; the "Ideal" is made in similar sizes, but only up to 380 H.P.

HARRISBURG STANDARD SIMPLE ENGINES (SINGLE VALVE).

Ind. H.P.	Cylinder.		Rev. per Min.	Diam. Pipes.		Pulley.		Weight including Base.		Approximate Floor Space.
	Diam.	Stroke.		Steam.	Ex.	Diam.	Face	Belted.	D. C.	
	in.	in.		in.	in.	in.	in.	lbs.	lbs.	ft. in. ft. in.
12	5	6	500	2	2	32 / 37	6½	3,000	3,100	6 0 × 3 6
26	7	8	425	2½	2½	42 / 46	8½	3,860	4,000	6 10 × 3 10
45	9	10	350	3	3	48 / 54	10 / 11½	6,000	6,300	7 10 × 4 8
95	13	11	325	4½	4½	54 / 62	11½ / 12	9,300	10,000	8 0 × 4 8
110	14	13	285	4½	6	54 / 66	12 / 16	13,500	14,400	10 2 × 5 8
150	15½	15	275	6	7	60 / 72	12½ / 20	18,300	19,300	11 9 × 6 6
200	18	16	250	6	7	60 / 72	12½ / 20	22,400	23,690	12 0 × 6 8
290	22	20	200	8	10	72 / 84	16 / 28	40,200	41,800	14 2 × 8 4
375	24	26	160	10	12	120	32	55,000	56,400	18 6 × 10 3
500	28	28	150	10	12	138	40	72,000	74,500	19 6 × 11 0
700	33	33	130	12	14	150	59	92,000	95,000	23 3 × 14 6
850	36	36	120	12	14	174	65	125,000	130,000	24 0 × 14 10

Indicated H.P. is based upon 80 lbs. steam pressure, atmospheric exhaust, and ¼ cut-off. Power at 90 lbs. pressure is one-eighth, and at 100 lbs. is one-fourth greater. The actual H.P. may be taken as 10% less than the indicated. There are 80

sizes of this type; the above table gives only the smallest, largest, and 10 sizes between.

In addition to this series of single-valve, simple engines, the Harrisburg Foundry and Machine Works build 47 sizes of "standard" single-valve, tandem-compound engines, from 21 to 1,110 H.P., with speeds of 450 to 120 r.p.m.; also similar "Ideal" engines up to 440 H.P. The four-valve, simple and compound types will be considered on page 177 under the head of "Medium Speed," and the Corliss simple and compound engines with steam-accelerated valves have already been described (p. 160).

The Westinghouse Engine is another type in which the working-parts are completely inclosed. The engines are made in three styles,—the "standard," which is the original form, the "junior," and the "compound" (Fig. 52). They are all similar in general construction, and consist of a pair of vertical cylinders bolted to the top flange of the crank-case, which latter serves the double purpose of a pedestal for the engine, and a receptacle for the oil, into which the cranks dip at each stroke. The pistons are of the trunk form, being open at the bottom, and are made sufficiently long (about $1\frac{1}{2}$ diameters) to serve as cross-heads, the connecting-rods being directly attached to them. In the "standard" the valve-chest is in the form of a third cylinder, which is in a slightly oblique position, and is often mistaken for a working cylinder. In the "junior" and compound engines the valve-chest is at right angles to the cylinders across the top. A single piston-valve is used in all of these engines, the valve-seat being a removable bushing in which the ports are milled.

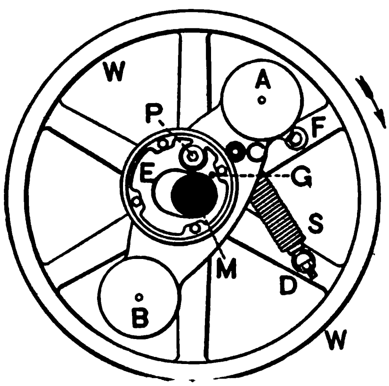


Fig. 51. Governor of Westinghouse Compound Engine.

In the "standard" engine the governor, which acts by centrifugal force only, is mounted on the shaft between the two cranks; in the "junior" engine it is located on the outside of one of the two fly-wheels, the valve being actuated by an eccentric

pin; and in the compound engine it is carried on the inside of one of the fly-wheels, the valve being operated by a disc eccentric. The two latter governors are of the inertia-centrifugal type, similar to that represented in Fig. 43. The form used on the compound engines is shown in Fig. 51. It consists of a single weighted bar (AB) pivoted on a pin (P) fixed to the hub of the wheel. A spring (S) is attached to the wheel with an adjusting nut at D and to the weighted bar at C. The centre of gravity of the bar being at G, increase in speed tends to make this point move away from the centre of the main shaft (M), and causes the bar to swing on its

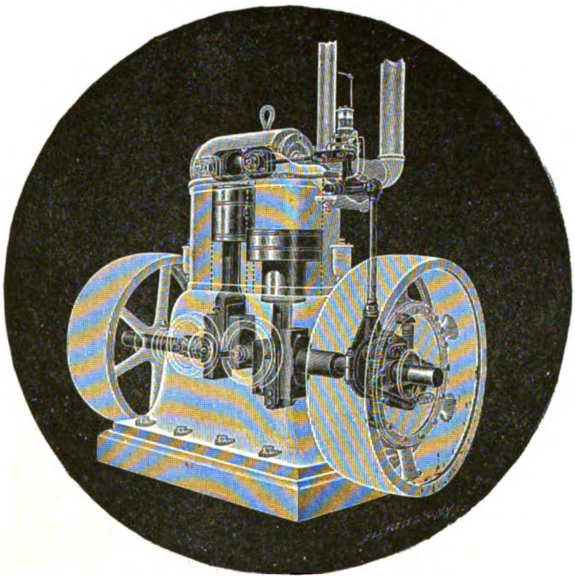


Fig. 52. Westinghouse Compound Engine.

pivot in a direction opposite to that of the arrow indicating the rotation of the wheel. The eccentric E carried by this bar is thus brought more nearly concentric with the shaft, and its angular advance is also increased so that the travel of the valve is less and the cut-off occurs earlier, the position shown being for latest cut-off. A sudden increase in speed will cause the bar AB, on account of its inertia, to lag behind the wheel, thereby producing the same effect momentarily as that resulting from centrifugal force—in fact the former may be said to anticipate the latter. The motion of the bar is limited by a stop at F and by the eccentric coming in contact with the shaft at E. Other facts con-

cerning this general type of governor have already been given in connection with Fig. 43.

The "standard" engine is made in 13 sizes, ranging from 5 to 250 H.P., the speeds being respectively 500 and 250 revolutions per minute. The "junior" engine is built in 7 sizes, from 5 to 75 H.P., and speeds of 400 to 330 revolutions per minute.

The compound (single-acting) engine is made in 9 sizes, from 35 to 250 H.P., and speeds of 375 to 250 r.p.m. (Fig. 52).

Willans Engine.—A high-speed type widely used in England, where it originated, and built also by the Bradley Manufacturing Company of Pittsburg, is the Willans central-valve engine. It possesses several unusual features, being in the first place single acting; that is to say, the steam pressure is exerted only on one side of the piston. The governor is of the simple throttle-valve form, the cut-off being set at a certain point and not controlled by the governor, whereas practically all American engines, whether high or low speed, are provided with an automatic cut-off. Another peculiarity is the location of the valve *inside of the piston-rod*, which is made hollow for the purpose. In spite of these apparent anomalies, the engine has been successful, and seems to possess advantages, the most prominent of which are —great compactness and economy in floor-space; avoidance of lost motion and knocking, owing to the fact that the steam pressure is always exerted in one direction; automatic and perfect lubrication of bearings and other working-parts, obtained by inclosing them in a chamber partly filled with oil; and, finally, high speed, being from 350 to 500 revolutions per minute. The economy of this type is very good, especially when its moderate size and very high speed are considered. It is made simple, compound, and triple-expansion; but usually only the two latter, with two sets of cylinders, are used in electric lighting.

The construction is shown in Fig. 53, which represents a pair of compound engines acting upon the same shaft. Each of the two sets of pistons is connected to its corresponding crank by a pair of connecting-rods, with a space between, containing an eccentric, forged directly upon the crank-pin.

Piston-valves are used, moving *inside of a hollow piston-rod*, which passes completely through the line of pistons, and through

the ends of the cylinders. The reason for placing the eccentric on the crank-pin, and not on the shaft as usual, is the fact that the valve-face (i.e., the inside surface of the hollow piston-rod)

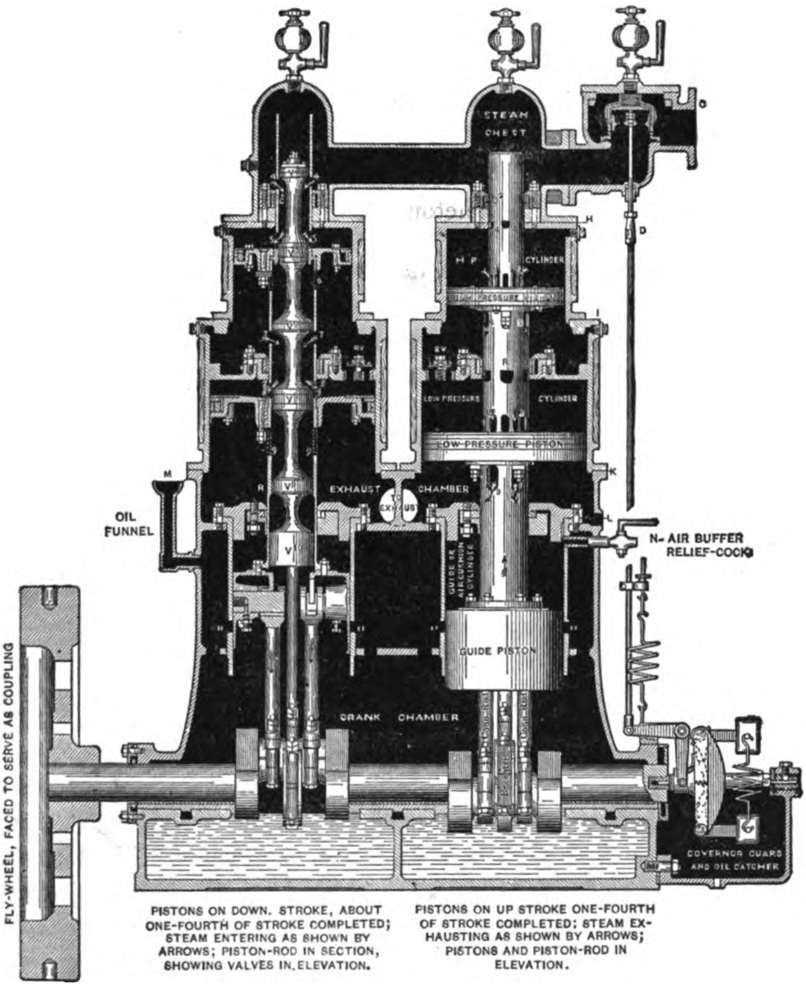


Fig. 53. Willans Central-valve Compound Engine.

moves with the pistons. Consequently the valve-motion required is *relative to the pistons;* and is obtained by mounting the eccentric on the crank-pin, which, like the piston-rod, moves with the pistons. Though its lead is different from that of an ordinary

eccentric, its effect upon the movement of the valves is practically the same. The action of the steam is shown in Fig. 54. It passes from the steam-chest into the hollow piston-rod, then out through ports in the latter into the high-pressure cylinder; on the return stroke flowing into the low-pressure cylinder.

The Case Engine is an example of a very high-speed engine adapted to being directly connected to dynamos for small electric plants. Fig. 54 shows a skeleton view of the internal arrange-

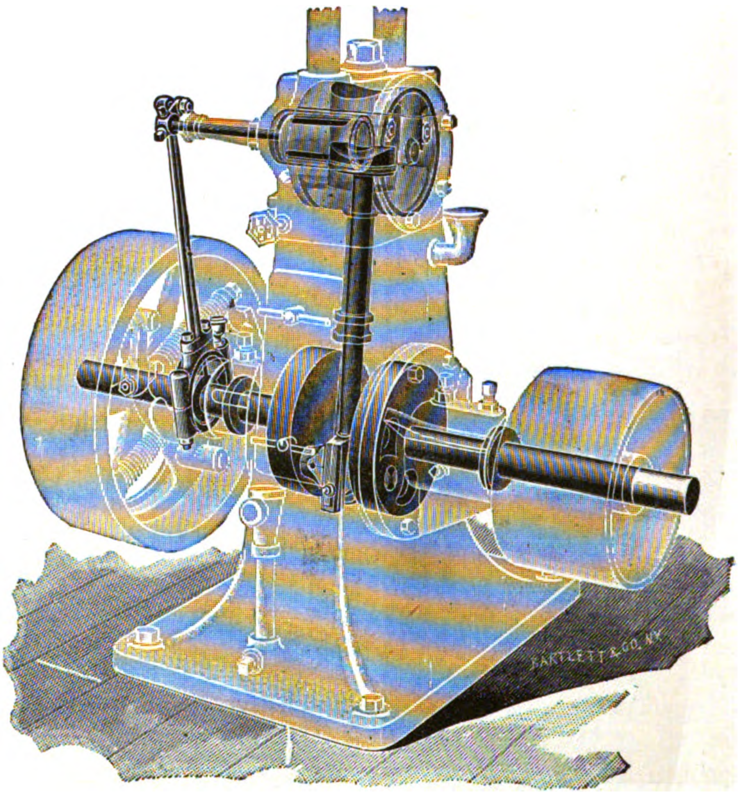


Fig. 54. Working-parts of Case Engine.

ment and working-parts of this engine, which are inclosed in a cast-iron box. The cylinder is of the oscillating type, being capable of rocking in its casing, which permits the piston-rod to be directly connected to the crank-pin, and saves weight in the moving-ports by eliminating the connection-rod and cross-head.

The cut-off valve is of the plug type, balanced and made with a slight taper, so that it can be kept tight. Its only duty is to define the point of cut-off; the admission, release, and exhaust closure being controlled by the rocking of the main cylinder, which thus performs the valve-action. The governor is of the usual shaft type, except that it does not vary the throw of the valve but rotates the eccentric on the shaft, thereby changing the lead. General experience with these engines proves that they regulate well, and any slight change in speed can be offset by compound winding on the dynamo.

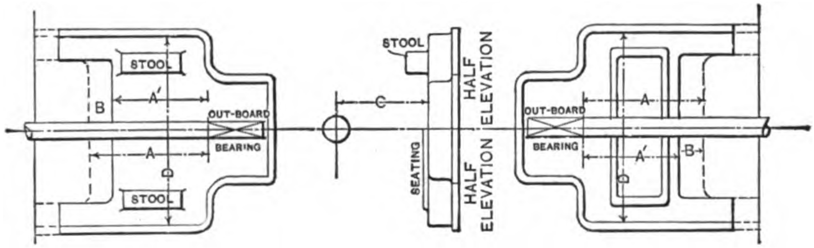
They are made in six sizes from 2.5 to 25 H.P. inclusive, with speeds from 900 to 550 r.p.m., being built in the pedestal form (Fig. 54); also in the bracket and hanger types, the two latter are mounted on the wall or ceiling where this may be desirable. For direct connection the pedestal form is bolted on a cast-iron base, to which the dynamo is also bolted, the two being connected by a flange coupling substituted for the wheel on the right in Fig. 54. In addition to the examples described other similar designs of high-speed engines are employed for driving electric generators, such as the Buckeye, Payne, Ames, Watertown, Skinner, McEwen, Chandler & Taylor, Atlas, Fitchburg, Buffalo Forge, Noye, and Reeves types.

Standardization of High-speed Engines and Dynamos.—The numerous sizes and styles of engines and generators of the various manufacturers resulted in great confusion, each builder being obliged to have many patterns to fit the different machines on the market. To avoid this trouble a committee of the American Society of Mechanical Engineers has made certain recommendations, which may be found in full in the Proceedings for 1901 and in the *Electrical World* of Dec. 7, 1901. The standard capacities, speeds, shaft diameters, and principal dimensions recommended are as shown in the table on page 178.

Medium-speed Engines.—Besides the types of high-speed engines just described, a third class of engines was defined (p. 156) to be those which are a compromise between the low-speed Corliss and the high-speed Ball engine, for example. These are vertical or horizontal and cross-compound or tandem-compound, the speed being ordinarily between 125 and 200 r.p.m.

STANDARDIZATION OF DIRECT-CONNECTED ENGINES AND GENERATORS.

RECOMMENDED BY THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS.



As arranged for horizontally parted generators.

Stools to be made and located to suit feet of horizontally parted generators. Builders of latter note that radius of outside of field piece must be ¼″ to ⅛″ less than "C."

As arranged for vertically parted generators.

Rectangular seatings to be made and located to suit bases of vertically parted generators.

Capacity of Unit K. W.	Revolutions per Minute.	Armature Bore.		Space occupied on Shaft between the Limit Lines.		B Length of Extension Pieces.	C Height of Axis of Shaft above Top of Base.	D Width of Top of Sub-base.
		Centre-crank Engines.	Side-crank Engines.	Long Class A	Short Class A′.			
		Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
25	310	4	4½	30	25	5	23	48
35	300	4	5½	33	28	5	25	54
50	290	4½	6½	37	31	6	28	60
75	275	5½	7½	43	37	6	31	66
100	260	6	8½	48	42	6	35	72
150	225	7	10	51	45	6	41	84
200	200	8	11	54	48	6	49	96

Five per cent. variation of speed permissible above and below speed in table.

Distance from center of shaft to top of base of outboard bearing may be less than "C" (to suit engine builder), though not less than possible outside radius of armature.

Up to 6 inches diameter engine shaft is $\frac{1}{1000}$ inch larger than armature bore, and over 6 inches diameter it is $\frac{2}{1000}$ inch larger.

An example of this class is the vertical cross-compound type built by McIntosh, Seymour & Co. and represented in Fig. 55. The admission of steam and the exhaust are controlled by flat gridiron valves actuated by an eccentric through rock-shafts and links designed to secure rapid opening and closing. The cut-off is determined by a third gridiron valve riding on the steam-valve and operated positively by a separate eccentric under the control of a shaft governor similar to that employed on the high-

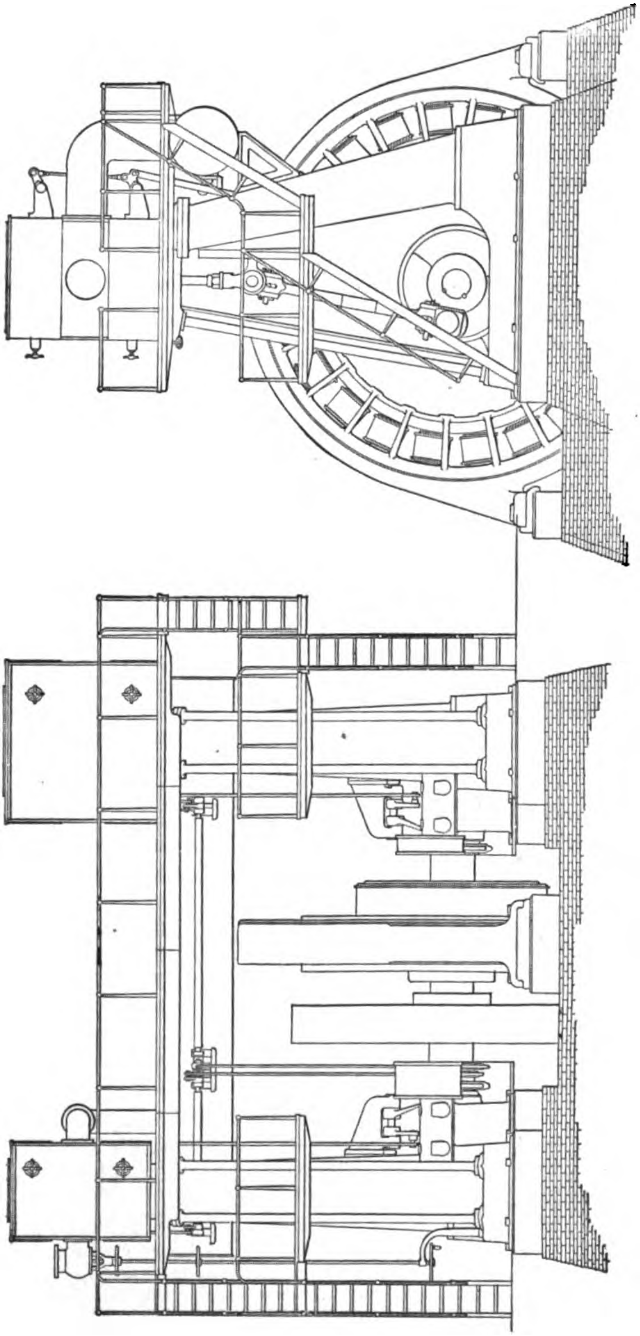


Fig. 55. Vertical, Cross-compound, Direct-Connected McIntosh & Seymour Engine.

speed engines already referred to (p. 168). These gridiron valves are claimed to have even less clearance than the Corliss form, and since they contain about twelve ports the motion required to obtain full opening, is only ½ inch for small sizes and 1½ inch for the largest engines.

Cross-compound engines of this type, both vertical and horizontal are made in 39 sizes, the smallest having cylinders 13 and 28 inches in diameter, giving about 300 H.P., while the largest has 30- and 46-inch cylinders, developing about 1,000 H.P. Each size may be built for 24-, 30-, 36-, 42- or 48-inch stroke, the speed of the smallest being 145 to 175 r.p.m. for the shortest and 70 to 100 for the longest stroke. There are larger engines in 24

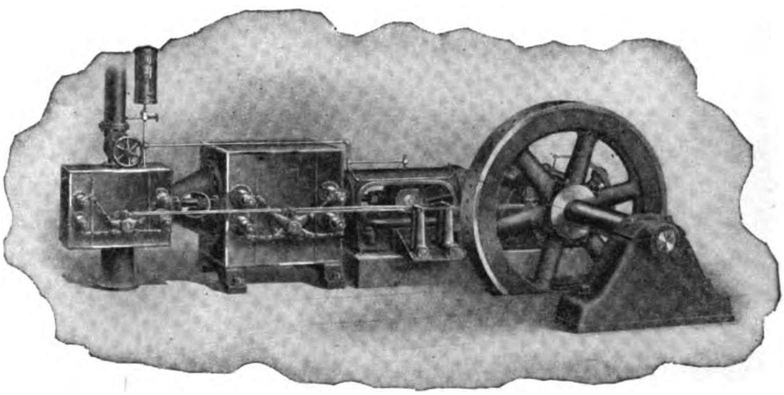


Fig. 56. Ball & Wood Tandem-compound Engines with Corliss Valves.

sizes, the smallest with cylinders 27 and 56 inches, giving about 1,200 H.P., and the largest with cylinders 41 and 82 inches, giving about 3,000 H.P. The stroke in this case is 30, 36, 42, 48, 54, 60, or 66 inches, depending upon the size of engine. This great variety of cylinder diameters, lengths of stroke, and speeds enable a selection to be made in accordance with the conditions: steam pressure, condensing or non-condensing, character of service, first cost, operating expense, etc. The 250 K.W. size of the type represented in Fig. 55 is 15 feet high and occupies a floor space 11 by 15½ feet; the 750 K. W. size is 25 feet high and 18 by 23½; the 2,000 K. W. size is 28 feet high and 21½ by 31, these being approximate dimensions.

Other well-known medium-speed engines are those built by the Ball & Wood Company and provided with Corliss valves that are non-releasing, being operated positively by eccentrics with the cut-off controlled by an inertia shaft governor similar to that on the high-speed engines (Fig. 47). They are made in the horizontal, tandem-compound form in 7 sizes from 125 to 375 H.P., and speeds of 215 to 235 and 180 to 200 r.p.m. respectively; also horizontal and vertical cross-compound engines from 300 to 1,200 H.P., with speeds of 180 to 200 and 130 to 150 r.p.m.

The Harrisburg four-valve engine is a prominent medium-speed design. It employs rotary valves actuated positively by eccentrics through bell-cranks that give rapid opening and closing, the cut-off being varied by an inertia shaft governor of the kind shown in Fig. 50. These engines are built either simple or tandem-compound, in many sizes, from 100 to 1,500 H.P. with speeds from 210 to 90 r.p.m. The Harrisburg Corliss engine has steam-accelerated valves intended to enable it to run faster than with the ordinary Corliss releasing gear. The cut-off is controlled by an inertia governor, but not mounted on the main shaft, being connected to it by belting to get the necessary speed. This type is made in the horizontal, simple, tandem-compound and cross-compound forms, the two latter in 26 sizes, from 410 to 1,850 H.P., with speeds from 160 to 80 r.p.m. (See p. 160.)

Steam Turbines *depend for their action upon the conversion of the heat-energy of steam into kinetic energy and in the transference of this kinetic energy from the steam to the rotating parts of the turbine.* In a general way they are analogous to the hydraulic turbines treated in Chapter XIV, the principle of operation and classification into parallel, outward and inward flow wheels being similar. With water, however, the kinetic energy is derived from the potential energy of hydrostatic pressure or head, and little change of temperature occurs, while with steam the pressure depends entirely upon heat. Furthermore, the volume of water is practically constant, whereas that of steam varies enormously. For example, 1 cubic foot of water produces 141 cubic feet of saturated steam at 200 lbs. absolute, 1,647 cubic feet at atmospheric pressure, and 25,500 cubic feet if expanded adiabatically from 200 to .6 lbs. abs. (28.7 inch vacuum).

In the last case 25.6 per cent of the steam would be condensed.

The much higher velocity of the fluid is the greatest difference between steam and hydraulic turbines. With a head of 50 feet the theoretical velocity of the fluid entering a waterwheel is only 80 feet per second. In steam turbines the velocity of the fluid is usually 1,500 to 4,000 feet per second, one reason being that the lower density demands higher velocity. A cubic foot of water moving 80 feet per second has kinetic energy

$$= \frac{mv^2}{2} = \frac{wv^2}{2g} = \frac{62\frac{1}{2} \times 80^2}{2 \times 32.2} = 6{,}210 \text{ foot-pounds.}$$

Dry saturated steam at 100 lbs. absolute pressure weighs only .23 lb. per cu. ft. instead of 62.5 lbs. for water, hence

$$\frac{.23 \times 1{,}320^2}{2 \times 32.2} = 6{,}210 \text{ foot-pounds,}$$

showing that its velocity must be 1,320 feet per second to give the same energy. The chief reason for high speeds in steam turbines is the physical fact that the particles in a steam jet move very rapidly. If 1 lb. of dry saturated steam at 285 lbs. abs. pressure be expanded adiabatically, doing work on nothing but itself, through a suitable divergent nozzle into a space in which the pressure is .6 lb. abs., 26.7 per cent of the steam is condensed, and the heat-energy given up is 386 B.T.U. Hence kinetic energy $= 386 \times 778$ ft.-lbs. and $1 \times v^2 \div 2g = 382 \times 778$, or $v = \sqrt{386 \times 778 \times 64.4} = 4{,}400$ feet per second. With a steam pressure of 200 lbs. abs. against atmospheric back pressure the velocity is 3,100 ft. per second, and into a 28-inch vacuum (.93 lb. abs.) it is 4,127 ft. per second. For 100 lbs. abs. pressure the velocities are 2,700 and 3,870 ft. per second respectively.

A steam turbine compared with a reciprocating engine has the same maximum possible efficiency as given by the expression $\frac{T_1 - T_2}{T_1}$, already discussed on page 76. The causes, however,

that make the actual efficiency fall below this theoretical value are largely different in the two cases. In reciprocating engines the greatest loss is usually due to cylinder condensation (p. 152), by which the cylinder walls cooled by the exhaust rob the entering steam of considerable heat. This cause of loss does not exist in the steam turbine, since the flow is continuous and in the same direction, some surfaces being in contact with the entering steam and some with the exhaust, but none with both. The "clearance" or spaces between the piston and the ends of the cylinder, also in the passages leading to the valves, occasions loss in reciprocating engines, but does not apply to turbines. Slide or rotary valves which may allow leakage of steam in engines are not used in steam turbines. Some steam leaks in the latter around the periphery of the wheels, since there must be a certain clearance for free rotation, but with many wheels, as in the Parsons or Curtis types, the leakage around the first is partly saved in the next, and so on. For the single De Laval wheel the initial expansion is nearly complete, and therefore little tendency to leak.

Friction in the best reciprocating engines causes a loss of 7 per cent or more, and in ordinary engines it is 10 or 12 per cent, owing to the number of moving parts, while in the turbine there need be only bearings for the shaft. Nevertheless, the chief loss in a steam turbine is due to the friction of the steam against the various surfaces and against itself, even when it is dry and at low pressure. With wet steam and high pressures the loss is much greater. Excessive friction would also be produced if water should accumulate by condensation and come in contact with the rotating parts. Even though the entering steam be perfectly dry it will be partially condensed and wet after it expands and does work, unless it is previously superheated. The efficiency of steam turbines is greatly increased (Fig. 60*a*) by superheating, and the gain appears to be more than thermodynamic principles would account for, the explanation being that it is partly due to reduced friction. An advantage of the steam over the hydraulic turbine is the fact that some of the heat generated by friction is restored to the fluid in the former, whereas it is wholly lost in the latter.

The use of a condenser raises the efficiency of a steam turbine even more than in the case of a reciprocating engine (Fig. 60*b*). This additional benefit is in part the result of diminished friction, but there are other important reasons. When the pressure of saturated steam is diminished from 5 to 1 lb. abs. the temperature falls from 162.4° to 102° F., whereas a lowering of pressure from 200 to 150 lbs. abs. reduces the temperature only from 381.6° to 358.2° F. (p. 90). Consequently there is great thermodynamic advantage in having a good vacuum in the condenser.

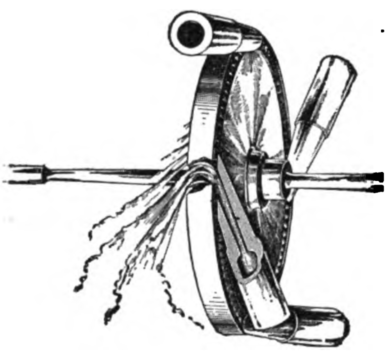


Fig 66a Principle of De Laval Turbine.

This gain is partly neutralized in the reciprocating engine by excessive cylinder condensation (p. 152). The steam turbine, being free from this trouble, benefits greatly by improved vacuum. A further limitation of the reciprocating engine is the practical impossibility of taking full advantage of a very good vacuum, because the volume of the steam increases so enormously (p. 90) that the bulk and friction of the engine would be excessive. Hence it is not practicable to obtain more than 10 to 20 "expansions." On the other hand, the steam simply flows through a turbine at very high velocity, so that 100 expansions can easily be reached without requiring the volume of the machine to be unduly large.

Economy at Light Loads is another point of superiority of the steam turbine. In the next chapter it is pointed out that the steam consumption of the best engines per H.P.-hour at one-quarter load is 60 or 80 per cent greater and often 100 per cent more than at rated load. A Curtis turbine is shown in Fig. 60*a* to require only about 18 per cent more steam per K.W.-hour at 150 K. W. than it does at rated load of 600 K. W.

The Motion of the turbine being rotary and constant, there is far less vibration and strain than in reciprocating engines, so that foundations may be much lighter and cheaper. The high and uniform speed of steam turbines is advantageous for driving alter-

nators in parallel since there is less tendency to "hunt" or vary in angular velocity.

Compactness is the most striking characteristic of the steam turbine, as illustrated in Fig. 60. It is chiefly due to very high speed, continuity of action, and distribution of strains.

The De Laval Steam Turbine.—The original form invented about 1883 was on the principle of Hero's engine, the modern type with expanding nozzle being brought out in 1889. The essential elements of the latter are represented in Fig. 56*a* and

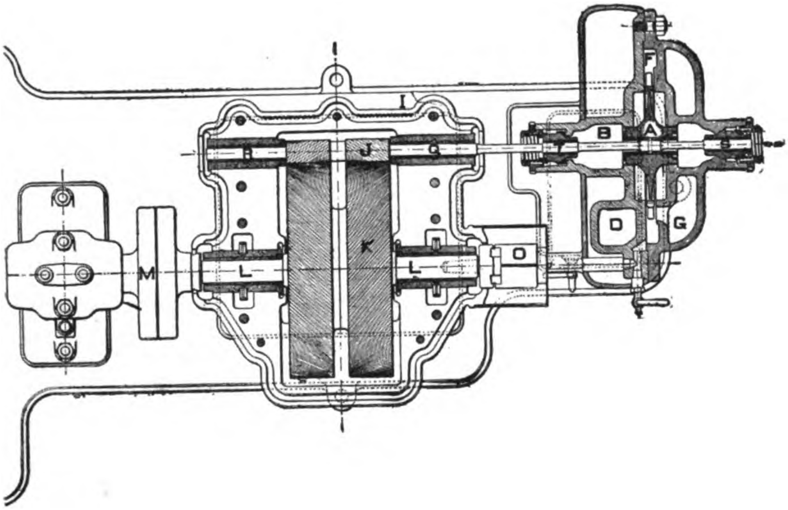


Fig. 57. Sectional Plan of De Laval 30-H.P. Steam Turbine.

consist of a single rotating wheel of steel with curved blades which form passages from one side to the other near the periphery. The steam impinges upon these blades from a number of nozzles with divergent orifices, one being shown in section. This form secures the very important result that the kinetic energy in the issuing jet is practically equal to work done on the piston of an ideal engine by the same volume of steam with equal ratio of expansion. In other words it converts heat-energy into mechanical energy as perfectly as the second law of thermodynamics allows (pp. 76 and 91). The section at the smaller end must be sufficient to pass the requisite quantity of steam, and at the larger end to obtain the proper expansion. If the nozzle

is too short there will be loss due to eddying currents in the jet and if too long friction becomes excessive. The nozzles are more numerous in the larger turbines, for example, the 225-H.P. size as built in England has 9 nozzles and as many as 15 have been used in still larger machines. The axis of each nozzle is set at an angle of 20° with respect to the plane of the wheel.

The high velocity of such steam jets has already been pointed out (p. 182), and was shown to be 3,100 and 4,127 ft. per second respectively when steam at 200 lbs. abs. pressure expands to atmospheric pressure or into a 28-inch vacuum (.93 lb. abs.). Theoretically the blades should have one-half the speed of the jet for maximum efficiency. The steam would then be delivered backward with respect to the blades at the same velocity with which they advance, so that the absolute motion is zero and all the kinetic energy given up to the wheel. Practically the steam leaves the blades at a considerable angle in order to flow away properly, and has an absolute velocity of about $\frac{1}{3}$ the initial; but it carries away only $\frac{1}{9}$ of the kinetic energy which is proportional to the square of the velocity. This principal is further explained in connection with hydraulic turbines (Fig. 68). Assuming 4,000 ft. per second for the jet, which is not uncommon, theoretically the blades should move about 2,000 ft. per second (22.7 miles per minute), but mechanical limitations due to centrifugal force, etc., reduce the actual speed to 10,600 r.p.m. or 1,380 ft. per second (15.6 miles per min.) for the 300-H.P. wheel, the diameter of which from center to center of blades is 30 inches, the peripheral velocity being 5 per cent. higher. The 5-H.P. wheel, with a mean diameter of 4 inches, turns at 30,000 r.p.m. or 500 ft. per second. The centrifugal force for each pound at 15 inches or 1.25 ft. radius is $\frac{mv^2}{r} = \frac{1 \times 1{,}380^2}{32 \times 1.25} = 47{,}600$ lbs. = 23.8 tons, and for each blade weighing $\frac{1}{28}$ lb. it is nearly one ton. To withstand this enormous stress the larger wheels are made thick near the center and taper toward the periphery, as shown in Fig. 57.

At these extreme speeds vibration is excessive unless the wheel rotates about its center of mass and it is practically impossible to obtain a perfect balance with respect to a fixed axis.

This difficulty is avoided in the De Laval turbine by using a long shaft of small diameter (Figs. 56*a* and 57) that is sufficiently flexible to permit the wheel to choose its own axis of rotation, which, above a certain critical speed, passes through the center of mass. The 5-H.P. turbine has a spindle $\frac{3}{8}$ inch in diameter and $1\frac{5}{16}$ inches for the 300-H.P. size, their torsional strength being ample to transmit the power at the very high speeds.

It is not practicable to run electric generators at 10,000 to 30,000 r.p.m., hence the speed is reduced by gearing to 775 and 3,000 r.p.m. respectively. In Fig. 57 the turbine A is mounted on the spindle RS of hard steel which carries two pinions J engaging with two gear-wheels K on the shaft L, the generator being directly connected to the latter by the coupling M. The gearing is double-helical, as represented, in order to reduce the noise and strains, the speed of the teeth being very high—about 100 ft. per second for all sizes. A comparison between the space occupied by the gearing JK and by the turbine A is striking. The eight sizes up to 55 H.P. are made in the general form shown in Fig. 57, but the five sizes from 75 to 300 H.P. have gear-wheels on both sides of the pinion driving two shafts, to each of which a generator is directly connected.

A centrifugal governor mounted on the lower-speed shaft regulates the flow of steam. In condensing turbines a valve controlled by the governor admits air to the turbine casing and thus varies the back pressure. This governor should act only for small variations in load because throttling the steam or admitting air reduces the efficiency; hence considerable changes in power should be effected by varying the number of nozzles in use. This may be accomplished by an arrangement similar to that employed for the Curtis turbine.

The friction of the steam against the rotating wheel has already been stated to be very considerable at high speeds, and is closely proportional to the density of the medium. The de Laval wheel, which is single, turns in steam at about atmospheric pressure for non-condensing and in a partial vacuum for condensing operation. This has been noted as an additional reason for using condensers with turbines. In the Parsons and

Curtis types with many wheels, the pressure is low only for the last ones, being quite high for the first.

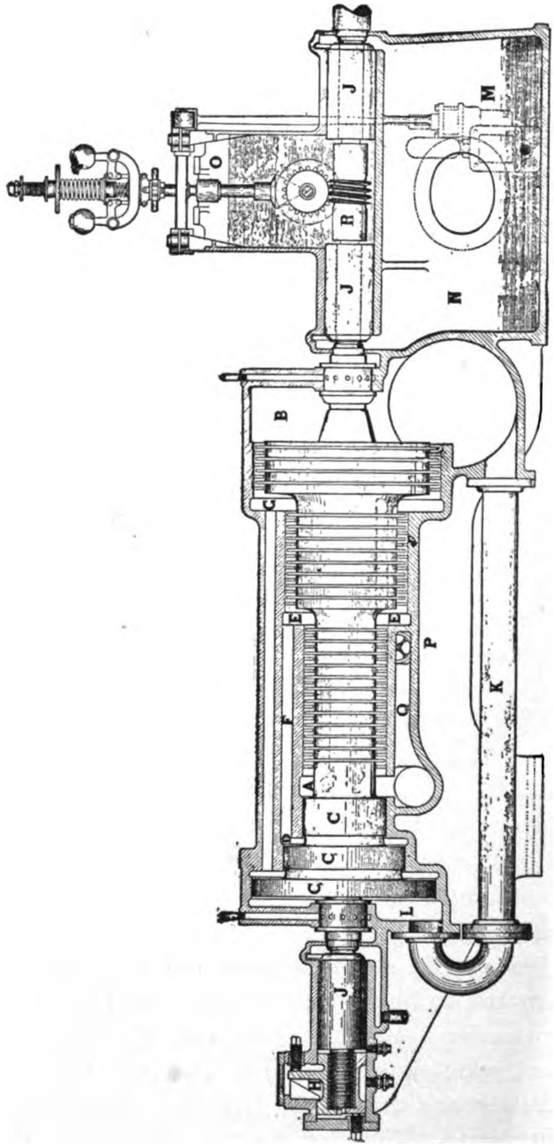


Fig. 58. Westinghouse-Parson's Steam Turbine.

The Parsons Steam Turbine, the original form of which was invented in 1884, differs radically from the de Laval type in hav-

ing many rings of blades instead of a single wheel, the general construction being shown in Fig. 58. The steam enters at *A* and passes to the right through the series of blades to the exhaust chamber *B*. There is first a set of stationary blades, then one of moving blades and so on alternately, similar to the Curtis arrangement represented in Fig. 59, but expanding nozzles are not employed at the influx or at later stages, the expansion being obtained by progressive enlargement of the passages. This is secured by increasing the depth of the blades, and when a practical limit is reached, the diameter of the wheel is made larger, as at *E* and G. On the left of the steam inlet *A* there are balance-pistons (*C*,*C*,*C*) corresponding to the different diameters of the turbine, being 1 to 4 in number according to size. These practically neutralize the end-thrust of the steam, a small thrust-bearing (*H*) being introduced to take care of slight inequalities. There is a little clearance around each piston, but the leakage of steam is small. A pipe (*K*) connects the back of the balance pistons at *L* with the exhaust chamber to equalize the pressure. There are three bearings (*J*,*J*,*J*), each comprising a gun-metal sleeve and three concentric tubes with small clearances between them. These fill up with oil and permit a very straight vibration of the shaft, so that it may rotate about its axis of mass, the result being similar to that obtained by de Laval's flexible shaft. The oil drains from the bearings into the chamber *N*, from which it is forced by the pump *M* into the reservoir *O*, to be used over again by gravity. A by-pass valve admits high-pressure steam through *Q* to the space *E*, enabling 60 per cent overload to be carried with somewhat reduced efficiency for emergencies or temporary conditions.

The governor is of the fly-ball centrifugal type (Fig. 58), and so arranged that in its middle position it admits full steam pressure. A movement in either direction tends to reduce the supply, so that in case of short-circuit or other excessive load the steam is shut off instead of being increased in amount.

The Curtis Steam Turbine consists of a series of stationary expanding nozzles *N* in Fig. 59, from which the steam passes successively through two or three rings of revolving blades *MM* on the rotating wheel, being placed alternately with rings of reversed

blades on the stationary element. A set consisting of several lines of moving and stationary blades, as represented, is called a stage, of which there are from two to five. The steam flows through these stages, being introduced each time through expanding nozzles formed in a fixed diaphragm that separates one stage from the

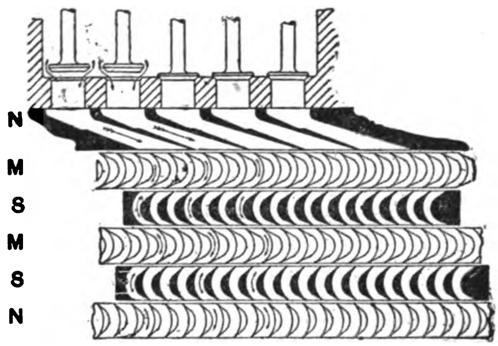


Fig. 59. Principle of Curtis Steam Turbine.

next. The total number of rings of moving blades *M* is usually from 6 to 10, being 8 for 2000 K. W.; consequently in this respect the Curtis type is a compromise between the simple de Laval wheel and the numerous rings of the Parsons turbine, of which there are 58 in the 375 K. W. size and about 70 in the 2000 K. W. size, as built by the Westinghouse Machine Company.

The diameter of the Curtis wheel is considerably greater than that of the de Laval or Parsons, being about 6½ feet for 500 K. W. and 12½ feet for 5000 K. W., compared with 2½ feet for the 200 K. W. de Laval, about 2 feet for the 375 K. W. Westinghouse-Parsons, and 6 feet for the 2000 K. W. turbine of that design, the last two being maximum diameters at the large end (Fig. 58). On account of increased diameter the speeds of the Curtis turbines are much lower than those of the de Laval or even Parsons type. The first runs at 1800 r. p. m. for 500 K. W. and 500 r. p. m. for 5000 K. W.; the de Laval at 20,000 r. p. m. for 20 K. W. and 10,600 r. p. m. for 300 K. W.; and the Westinghouse-Parsons at 3600 r. p. m. for 375 K. W. and 1000 r. p. m. for 2000 K. W. The speed of the blades in the Curtis wheel is between 300 and 400 feet per second;

for the 200 K. W. de Laval it is 1380 feet per second; and about 200 to 300 feet per second for various sizes of Parsons turbines.

The governing of the Curtis turbine is effected by opening and closing the nozzles, two of which are shown open and three closed in Fig. 59, the total number being from 4 to 20 in each stage. The nozzles of the later stages may be operated in correspondence with those of the first stage, some improvement in light-load economy being thus secured; but usually the gain is small and does not warrant the complication involved. In some cases an approximate adjustment is maintained by automatic valves in later stages which control the nozzles in accordance with the pressure behind them. These are introduced as much to limit the pressures in stage chambers as to improve the light-load economy. The governor is of the fly-ball centrifugal type, connected by a steel ribbon to a device that opens and closes the various nozzles. In some cases the nozzles are operated electromagnetically and in others by steam relay valves.

For direct connection with electric generators the Curtis turbine is usually made in the vertical form represented in Fig. 60. The step bearing that carries the weight of the moving parts is very simple and successful. It consists of an enlargement AB at the foot of the main shaft CD which rests on a flat surface EF (Fig. 60*c*). Oil is pumped into the central space G under a high pressure somewhat greater than the weight carried per square inch of surface, the shaft being actually lifted from .004 to .010 inch, so that it floats upon a film of oil. The moving mass of the 5000 K. W. turbine weighs 64 tons, yet the friction is so small that it can be turned by applying one finger to the periphery of the wheel, which is 12½ feet in diameter. In case the pump fails, there is an automatic stop, but the effect of shutting off the oil supply is merely to wear off the surfaces about .01 inch, without serious harm. It is also found that water at high pressure may be used instead of oil. The flow of oil or water is small, the power required to drive the pump being much less than 1 per cent of the total output of the generator.

The combined turbine and 5000 K. W. alternator are 14 feet 10 inches in diameter at the base and 25½ feet high above the floor. In Fig. 60 this combination is compared in size with a Corliss

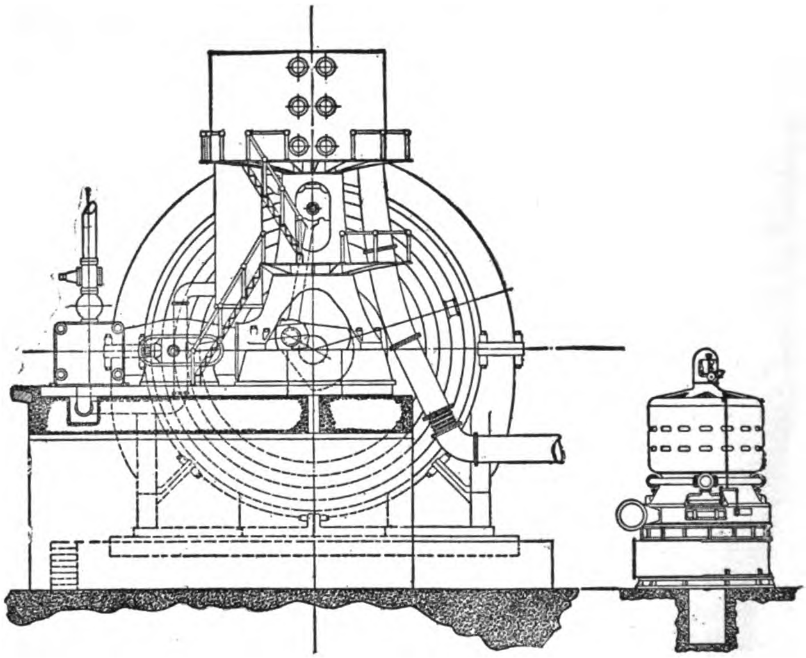


Fig. 60. Comparison of 5000 K. W. Engine and Curtis Steam Turbine.

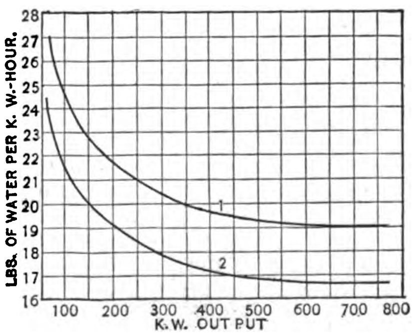


Fig. 60a. Curtis Turbine without and with Superheating.

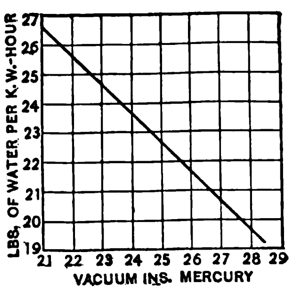


Fig. 60b. Curtis Turbine with Different Vacua.

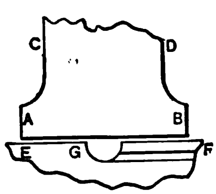


Fig. 60c. Step Bearing.

engine also directly connected to a 5000 K. W. alternator as installed in the Manhattan Railway power station, New York City. The speed of the former is 500 and of the latter 75 r. p. m., which largely accounts for the great difference in size, the total weights in the two cases being in the ratio of 1 to 8.

The curves in Fig. 60*a* give results obtained from a 600 K. W. Curtis steam turbine at 1500 r. p. m., under 140 lbs. pressure, a vacuum of 28.5 inches, without superheating (1) and with 150° F. superheat (2). It is shown in Fig. 60*b* that the economy is improved in direct proportion to the vacuum in the condenser. In other words, the turbine takes full advantage of the highest degrees of expansion, the reciprocating engine being limited in this respect, as already pointed out.

The Rateau Steam Turbine resembles the Parsons type in having many rings of blades of moderate diameter mounted upon a long shaft, but differs from the latter in the respect that each ring of blades revolves in a compartment of its own. The object of this construction is to avoid leakage, which is one of the chief difficulties in these machines. It has been explained that the initial expansion is practically complete in the de Laval wheel, hence there is little difference in pressure to produce leakage. On the other hand, a single wheel must run at extremely high speeds. In the Parsons turbine peripheral speed is reduced by employing many wheels, but these involve differences of pressure and leakage between each space and the next. This is not all loss, because steam that leaks at one point may be utilized later; nevertheless the clearances are made so small that almost perfect design and workmanship are demanded, and even then trouble often results. A Curtis turbine has two to five "stages" separated by diaphragms to reduce leakage, with two or three rings of moving blades in each. The Rateau arrangement separates each wheel from the next by a diaphragm, which involves more complicated construction.

Difficulties with Steam Turbines are chiefly due to the small clearances considered above, and to high speeds. Expansion of the parts, especially with high pressure and superheated steam, is likely to allow the moving parts to strike or rub against the stationary parts. Unequal expansion of the frame may also cause the bearings to bind the shaft and prevent its free rotation.

CHAPTER XII.

STEAM-ENGINES FOR ELECTRIC LIGHTING.

SELECTION, INSTALLATION, AND MANAGEMENT.

THE selection of the best size and type of steam-engine for a given electric lighting plant is, next to the choice of the system itself, the most important question which the engineer has to decide, since the satisfactory operation and working expenses of the station are directly dependent upon it.

The number of units in large central stations, whether steam-engines or dynamos, should be sufficient so that the disabling of one will not interfere with the proper running of the station; and, if possible, the number and size of units should be such that two of them may break down, and still allow the plant to carry its full load. The same idea may be expressed somewhat differently by stating that no unit should be more than one-quarter to one-tenth of the total capacity of the plant, and there should be one or two spare machines. In very small plants it is obviously impracticable to subdivide the power into many units, but, even in that case, it is always desirable to have at least two engines; and, if possible, each of them should be capable of carrying the ordinary load, or such a large fraction of it, that a sufficient number of lights can be run to give a reasonable supply, and not cause serious inconvenience in case of a stoppage of one engine.

In central stations of medium size the number of engines should be intermediate between those of a large station and a small plant, that is, from 3 to 6. There are exceptions to these general rules, some stations having one or two very large engines connected to a few large dynamos, or to a number of small ones. This plan has the advantage of simplicity and low first cost; but it has the disadvantages of practically shutting down the station if anything happens to one engine, and the economy of running a large engine during periods of light load would be very low. In fact, one or two auxiliary engines of smaller size would be a

very desirable addition to such a plant, not only as a safeguard in case of a breakdown of the main engine, but also for use when the load is small. This would make the total number of engines about three or four.

The relative size of the units, that is, the question whether they should be of the same or of different power, is often a perplexing point. The chief advantage of uniformity in size is the interchangeability of parts, and the possibility of having one or two spare parts which can be used in any engine that may happen to require them. On the other hand, the adoption of engines of different sizes may result in greater convenience and increased all-day efficiency of the plant; for example, in an isolated plant with which the author is familiar, there is one engine and dynamo of 750 lights capacity, and one of 250 lights, giving a total capacity of 1,000 lights. During the day and late at night the smaller engine can be run very economically with the load, which varies between 100 and 200 lights. When the load increases at the approach of darkness, the larger engine is substituted for the smaller, and supplies power for the 500 to 700 lights which are used during the evening. In this way each engine is almost perfectly suited to its load for long periods of time, the interval between the light load of the day and the heavy load of the evening being so short that the larger engine has to run for only a few minutes at an uneconomically light load; and for an unusually large load both engines can be run at the same time. In the design of central stations a similar judicious selection of engines may give excellent results. For instance, large compound or triple-expansion engines may be operated almost continually to carry the permanent portion of the load with high economy, but for the maximum load, which usually lasts only an hour or two, cheaper and simpler engines may be used.

A little ingenuity and judgment will suggest many other similar plans by which convenience and efficiency can be secured. Careful adaptation of the size, number, and type of the engines will largely overcome the serious drawback of low economy in electric-lighting plants, which arises from operating steam-engines with light loads and variable loads. In nearly every case it would be possible to so select the engines that at no time would any one or more of them be running below 60 or above 125 per cent of

its normal load. The latter limit is allowable, at least temporarily, and avoids the very low efficiency that results from running an engine at a small fraction of its full power. This arrangement might not be possible where the variations in load are very sudden, as in small electric-railway plants; but in electric lighting, especially with large installations, the changes are usually gradual and almost always allow time to put on or take off engines.

This scheme would serve to accomplish practically the same result as the use of storage batteries in enabling the engines always to be run at high efficiency, and would avoid the complication of storage batteries and the loss of energy which occurs in charging and discharging them. In some cases the carrying out of this idea might be difficult, either because the load is continually varying throughout the entire twenty-four hours of the day, or because the number of lamps connected to the station might increase so that a proper proportion in the size of engines in the beginning might not be right a few months afterwards; and the conditions would also change greatly with the season of the year. This, however, could be foreseen more or less, and could be provided for in originally planning or increasing the capacity of the plant. This matter is treated further in connection with storage batteries in Chapter XXI.

In general it may be stated that in central stations or large isolated plants it is allowable, and may be desirable, to have two sizes of engines. But more than this are objectionable. Many plants are in the unfortunate position of having installed several different sizes and types of engines at various periods of their history, corresponding to the conditions existing at each time. In many cases this cannot be helped; but often a little foresight will save a plant from becoming a museum, which represents by numerous examples the progress of steam and electrical engineering.

The type selected is largely determined by the size, small engines being usually simple, and larger ones compound. Similarly, small engines may have high speed, and large engines should be of low or medium speed. If floor-space is valuable or limited, a vertical engine or steam turbine may be chosen. The matter of direct driving, belting, and other forms of connection between engine and generator is fully discussed in Chapter XV, but the first has now become almost universal.

The proper size, number, and type of electric generators to select is considered in Chapter XIX; but the question is not so important as in the case of engines, for the reason that the former can be run at half or even one-quarter load without serious impairment of efficiency. It is also a fact that they can be started and stopped much more quickly and easily than a steam-engine, and without the loss of energy involved in heating up the latter. Furthermore, a generator can be run free with about 4 to 6 per cent of full power even when the field-magnet is excited, and with about 3 per cent if the field is not excited, whereas the friction of a steam-engine is 7 to 12 per cent of its rated power; hence there is much greater likelihood of mistake and loss in selecting or handling steam-engines.

The relative advantages of simple and compound, also condensing and non-condensing engines, the electric-light engineer is called upon to determine. Authorities often disagree on these questions, because so much depends upon the particular type and size of engine, and the conditions of use in each case.

Simple and compound engines have already been compared in a general way on page 152. In the actual selection and use of an engine the simple or single-cylinder type has the great advantage of simplicity. This is particularly important in smaller sizes, and below about 50 horse-power it is doubtful if the saving in coal by a compound engine is worth the increased first cost and care which the additional complication involves. When, however, the size of an engine becomes considerable, it is a positive advantage to increase the number of parts in order to reduce the weight of each, so that they are more easily handled in building and repairing the engine. For vertical engines in particular it is evidently better in appearance and construction to have two or more cylinders arranged side by side than to have one large and clumsy cylinder.

The chief merit, however, claimed for compound engines is their higher economy; but it has already been pointed out (page 154) that a great deal of this gain is due to the higher steam pressure *per se*, and that the economy of a simple engine is also considerably raised by increased pressure. The principal objection to the use of simple engines with high pressures, and therefore high temperatures, is the great range of temperature that tends to cause large losses by cylinder condensation (p. 152).

Another advantage of multiple-cylinder engines is the distri-

bution of strains; and for incandescent lighting the flickering of the lamps due to variation in speed at different points of stroke is practically avoided by having two cranks acting at 90°, or, better yet, three cranks at 120°. These arrangements are also better for operating alternators in parallel. Some types of compound engine, as, for example, the tandem-compound, have only a single crank, or the cranks act at the same angle, or at 180°, and the effect of the "dead center" is the same as in a single-cylinder engine.

Condensing-engines have already been discussed on page 147. In general it may be said that they are desirable, provided a suitable supply of condensing water is available and reliable, and provided the size of the plant warrants the expense and complication of condenser, pumps, connections, etc. The condenser has the effect of reducing the back pressure 12 to 14 lbs. below that of the atmosphere, which corresponds to a vacuum of about 24 to 28 inches of mercury. It is important, however, to note that the difference in *temperature* between steam at atmospheric pressure (14.7 lbs. absolute) and at a condenser pressure of 1 lb. absolute is $212° - 102° = 110°$ F.; whereas the difference in temperature of steam at 114 lbs. and 100 lbs. absolute pressure is only $337.2° - 327.6° = 9.6°$ F., which is less than one-tenth as much. For higher pressures the temperature difference is still less for a given difference in pressure. Hence the efficiency gained (see page 91) by reducing the pressure at the lower limit is far greater than by increasing it at the upper limit. This is clearly shown in indicator diagrams, where, for example, the area included between the lines of 10 and 20 lbs. pressure is usually much greater than between 60 and 70 lbs., as represented in Fig. 61. The losses by conduction and radiation are also less in condensing engines with a given effective pressure, since the average temperature is nearer that of the atmosphere. For steam-turbines the condenser is particularly important, as shown on pp. 184 and 192.

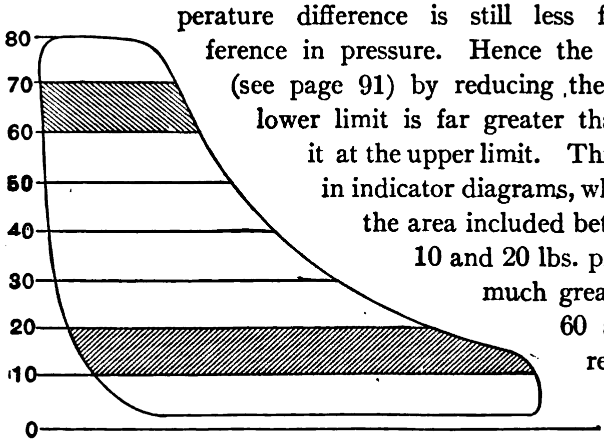


Fig. 61. Power Corresponding to Different Ranges of Pressure.

The best point of cut-off is almost always given as being between $\frac{1}{4}$ and $\frac{1}{5}$ of the stroke for a simple engine, and about $\frac{1}{3}$ for compound engines. An earlier cut-off is considered objectionable because it increases the ranges of temperature, and therefore cylinder condensation. The cut-off which gives the least steam consumption per horse-power may be raised somewhat in practice because the power of the engine increases with the cut-off (not proportionally, however) and a proper compromise between running expense and first cost should be made. Moreover, engines usually run much of the time below rated power, hence the average load would correspond more closely to the most economical point of cut-off.

A steam-jacket around the cylinder is often recommended to reduce cylinder condensation, but it is seldom used in practice.

Superheated steam is also highly recommended for the same reason; but it is not very commonly employed, owing to the difficulty of obtaining it. The decided improvement in steam-turbine economy due to superheating has led to its more frequent use in that case (p. 184 and Fig. 60*a*). The subject of superheated steam has been treated by C. A. Hutchinson and by E. H. Foster.*

ECONOMY OF STEAM-ENGINES WITH VARIABLE LOADS.

In electric lighting many plants are run for a large part of the time at light load. The effect of this on the economy of an engine is very detrimental; the result being that the coal consumption in many electric-light stations, as well as small plants, is about twice as great as if the same total number of horse-power hours were developed by engines running uniformly at full load. Professor R. C. Carpenter has discussed this important matter quite fully in a paper on "The Variation in Economy of the Steam-engine due to Variation in Load."† He gives the pounds of water per horse-power hour required by the various types of engine with $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$, and $1\frac{1}{2}$ times their rated capacity; and the general fact is that the steam and also coal consumption per horse-power are 30 to 50 per cent greater at $\frac{1}{2}$ load than at the rated load, and are about twice as great at $\frac{1}{4}$ load. It is claimed that the best

* *Trans. Amer. Soc. Mech. Eng.*, May, 1901.

† *Trans. Amer. Inst. Elec. Eng.*, vol. x., May 17, 1893.

engines consume only 70 or 80 per cent more steam per H.P. at $\frac{1}{4}$ load, but in most cases 100 per cent is nearer the fact. This applies to actual or brake H.P. and not to indicated H.P. The variation in economy is not great between $\frac{3}{4}$ and $1\frac{1}{4}$ times the rated load; but beyond these limits, particularly below, the increase in steam consumption is very rapid, and we should therefore carefully avoid operating an engine except within this range of power. It was pointed out in the beginning of this chapter that a judicious selection of the type, number, and size of engines will usually enable each engine, while in operation, to be run within the economical limits of load.

The friction of most steam-engines is between 7 and 12 per cent, and does not vary greatly for different loads. The higher figure is for condensing engines and includes, as it should, the friction of the air-pump. Friction is such a large factor in engines that it makes a great difference whether we consider indicated power or developed power. For example, at $\frac{1}{4}$ of the indicated load the actual power is only about $\frac{1}{8}$ of the full value, and the corresponding economy is extremely low.

The mistake of running steam-engines underloaded is very common, and is responsible for a large part of the inefficiency of electric light and power plants. The point of maximum efficiency is almost always made to correspond with the maximum load, whereas it should approximate the *average* load, since the full load may only exist for a few minutes each day. In other words, the engine should develop the average power at the best point of cut-off, as already stated on the preceding page. Moreover the efficiency is not reduced as much by overload as by underload. Engines consume only 5 or 10 per cent more steam per H.P. when 50 per cent overloaded; but they require 30 to 50 per cent more steam per H.P. at half-load. An engine is not injured by overloading, the only effect being to decrease its speed, which may be counteracted by raising the steam-pressure, or by regulating the dynamo. This plan would also save in first cost, since the rated power would be four-fifths of the maximum output, assuming only 25 per cent overload capacity. When designed to run with temporary overloads they are often called "heavy duty" engines, as described in Chapter XI.

With a light load the low-pressure cylinder of a non-condensing compound engine performs little or no work, because the governor allows only a small weight of steam to be admitted to the high-pressure cylinder. If, for example, the quantity of steam is such that it expands to atmospheric pressure in the first cylinder, then the piston of the second cylinder must do work against the back pressure of the atmosphere, and thus acts as a drag. Even with a heavier load, when the action of the second cylinder is not entirely negative, it would be desirable to disconnect it in order to eliminate its friction and complication. In a condensing-engine, on the other hand, the back pressure is largely removed and the second cylinder always performs part of the useful work. Hence, for light or variable loads, it may not be desirable to employ compound engines except with condensers.

Foundations for Steam-engines.—These have already been considered on page 59, and the means for avoiding the transmission of vibration from the engines were there explained.

The setting of the engine upon the foundation, and adjusting all of the parts in perfect alignment, should be carried out in the most careful manner. Almost all engines of 100 horse-power or less are provided with a cast-iron frame or base, upon which all the parts are mounted, and which makes the engine self-contained. This facilitates the setting of the engine, and avoids the possibility of the pillow-block or other parts getting out of line by the settling of a portion of the foundation. In very large engines, particularly if horizontal, it is not ordinarily practicable to mount hem entirely upon one base; and one pillow-block or bearing is mounted on a separate foundation, in which case it is of vital importance that the foundations themselves, and the ground upon which they rest, should be perfe tly solid, and free from danger of unequal settling. Progress is in the direction of heavier frames and more complete cast-iron bases, or bed-plates. In larger sizes these are made in sections united by links.

The practical laying out and building of engine foundations is best carried out by making a complete template, or frame of wood, as already represented in Fig. 7. The builder of the engine should furnish a drawing by which this template may be made, so that it will hold the various bolts in exactly the proper positions while

the brickwork is being built around them. This enables the foundation to be made ready to receive the engine as soon as it arrives, thereby avoiding considerable delay. It is well to surround each bolt with an iron pipe large enough to allow a slight play, otherwise there is likely to be difficulty in introducing the bolts into the holes in the engine base.

Lubrication of Engines.—Various kinds of oil are used to lubricate the bearings or other moving parts of machinery. These may be divided primarily into vegetable, animal, and mineral oils; but only the two latter are suitable for the purpose. The introduction of mineral oil is comparatively recent, sperm, lard, or some other form of animal oil having been used exclusively as lubricants, and even at the present time many engineers prefer them; but improvements in the manufacture of mineral oil, and its more extended use, have resulted in its being acknowledged to be as good as, or even better than, animal oil for machinery. Animal as well as vegetable oil is likely to be decomposed, with the formation of some organic acid. This change is what is commonly known as becoming rancid. The acid thus formed will corrode iron or other metal, which would be extremely objectionable in the case of a shaft or bearing. Mineral oil, on the contrary, does not form acid or any other deleterious substance, and for that reason is preferable to animal oil. It is usually much cheaper than animal oil of equivalent quality, and can be obtained of any desired viscosity.

The *quality* of oil is of the highest importance, and nothing is more foolish than to attempt excessive economy in this direction. The high cost of machinery, and the great importance of having it run as perfectly as possible, demand that only first-class oil should be used upon it. This is particularly true of cylinder oil, which is used to lubricate the valves, interior of cylinder, piston, and piston-rods, which are the most delicate parts of an engine. Engines may be lubricated by means of a number of oil-cups placed where required. These usually have a sight-feed: that is, the drops of oil which they supply can be seen and counted so that they can be adjusted by a screw or other device to the proper rate. Parts in motion are lubricated either by oil-cups placed upon them which are filled before starting, or by some form of "wiper" which scrapes off a certain amount of oil from a piece of felt or wicking

at each stroke. The cylinder lubricator is also an important attachment to an engine. In some forms of engine the lubrication is effected not by oil-cups, but by inclosing the moving parts and causing them to run in oil, or splash it about so that it is carried to the crank-pin, bearings, and other parts. Such forms are shown in Figs. 49 and 53.

A complete circulating system of lubrication is sometimes employed, and is an excellent method in plants of sufficient size to warrant its use. It comprises a small pump, operated from one of the engines or by an electric motor. The pump forces the oil up to a reservoir, from which it flows, by gravity, through small pipes to the different parts of the several machines; thence it runs back into a receptacle, from which it is again pumped into the upper reservoir.

In the Ball & Wood, Payne, Skinner, and some other types, each engine is provided with its own oil reservoir and piping. In these systems, whether general or individual, the separation of the oil from the water is effected by gravity, and it is also filtered to remove particles of metal or dirt. In circulating systems the separation of water and the filtering are usually automatic. In practically all cases oil is used over and over again.

CHAPTER XIII.

GAS- AND OIL-ENGINES.

The advantages of the gas-engine over the steam-engine are:—

1. Cleanliness and freedom from drip, ashes, smoke, and other objectionable accompaniments of the steam-engine.
2. The boiler and the danger of boiler explosion are eliminated.
3. Higher efficiency at all loads and probability of much higher efficiency.
4. Gas can be carried long distances economically, while with steam losses by condensation are large even at short distances.
5. Much more energy can be stored in gas than in the same volume of steam and without any loss.
6. Gas-engines may be started without waiting to make a fire and get up steam.
7. There is much less loss of energy in starting and stopping gas-engines, and there is no waste during the time that they are idle.
8. They may be run on waste gases, as in the case of blast-furnace plants.

The disadvantages of gas-engines are:—

1. They require some auxiliary means of starting.
2. They may stop if overloaded, and have to be started again as in No. 1.
3. The cylinder in most cases must be water-jacketed to prevent its walls from becoming too highly heated.
4. Many gas-engines, especially for moderate power, being single-acting or half single-acting, are more bulky than the corresponding steam-engines.
5. Single-acting or half single-acting engines require heavier fly-wheels to secure steadiness of motion.
6. The speed governing of gas-engines is not yet perfected to the same degree as that of steam-engines.
7. Possible difficulties with the ignition system.

Gas-engines are practically all of the explosive type; that is, a mixture of combustible gas and air is introduced into the cylinder, and there ignited by an electric spark, an incandescent body, or by high temperature due to compression. The high pressure resulting from the explosion acts upon the piston in the cylinder, and causes it to move and do work.

The series of actions performed upon and by the gas is called a *cycle*, the various kinds of cycles that might be employed being numerous. Of these the most prominent is the Otto or Beau de Rochas cycle, in which the operations are as follows :—

A mixture of gas and air in the proper proportion is drawn into the cylinder by a stroke in one direction. On the return stroke the mixture is compressed. It is then ignited at the beginning of the next forward stroke, during which it exerts a much higher pressure upon the piston; and on the next back stroke the products of combustion are expelled from the cylinder : thus the cycle comprises four separate actions; and four single strokes, or two complete revolutions, are required for each explosion or active stroke. Strictly speaking, therefore, such an engine is half single-acting, and a heavy fly-wheel is necessary to keep up the speed during the interval between the working-strokes.

This is commonly known as the "four-cycle" method, but is more properly a cycle consisting of four operations, sometimes called phases, each of which occupies one stroke.

In the "two-cycle" method the exhaust is effected by the piston uncovering a port near the end of its stroke, so that the products of combustion rush out, they being at this moment about 50 lbs. above atmospheric pressure. At the same time a new charge of gas and air is forced into the working cylinder under 5 or 10 lbs. pressure produced in other cylinders, as in the Körting engine, or by enclosing the crank chamber, as in the Mietz and Weiss engine. The return stroke of the piston compresses this charge, which is exploded at the beginning of the next stroke, and performs its work. Thus each alternate stroke is a working-stroke, and therefore the action is equivalent to that which occurs at one end of a steam-cylinder. "Two-cycle" gas-engines are often made double-acting, that is, the operations described take place on both sides of the piston, hence work is performed at every stroke, the same as in the ordinary double-

acting steam-engine. Furthermore, the mean effective pressure of the gas is much greater than that of the steam, so that the cylinder volume and bulk of engine are smaller, except for such auxiliary apparatus as may be necessary.

Advantages of Compression. — All explosive engines expand the burnt gases to the same volume that was occupied by the mixture before compression began. In a cycle as represented in Fig. 62 the series of operations are as follows:—

From A to B compression.
From B to C explosion.
From C to D expansion.
From D to A exhaust.

If now compression be carried to a higher pressure than before, say to B', then on explosion the pressure will rise to a higher value than C, say C', and there will be added to the work done an area $CC'D'D$; while the extra compression subtracts the area $BB'A$ from the area originally obtained by low compression. It can be easily shown that the gain $CC'D'D$ is always greater than the loss $BB'A$, so that increased compression before explosion will always give more work with the same fuel.

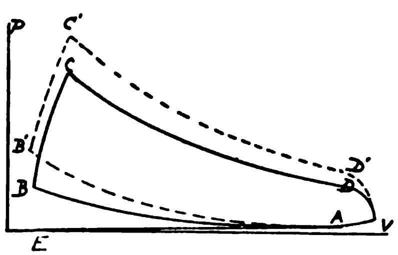


Fig. 62. Gas-Engine Cycle.

Analytically the same thing can be shown, the efficiency of such a cycle being $E = 1 - \left(\frac{V_b}{V_a}\right)^{.4}$, in which

V_b = volume of gas after compression,
V_a = volume of gas before compression.

So that the efficiency and work done with a given amount of fuel becomes greater as the ratio $\frac{V_b}{V_a}$ is made less or as the compression volume is made smaller, with greater compression.

The ignition of the gas is usually effected by an electric spark; an incandescent tube; or by the heat due to compression. The first is produced either by separating two contact points and breaking an electric circuit, or by applying a high potential and forcing a spark across a fixed gap. The electric spark may fail owing to corrosion or dirt on the contact points. The second device consists of a tube of nickel steel or porcelain, which connects with the cylinder, and is kept red-hot by a Bunsen burner. These tubes may last two or three years, but in some instances they burn out rather rapidly. Ignition in several types of gas-engine is produced by carrying the compression high enough. The chief difficulty with hot-tube methods is to cause the gas to ignite at the proper point in the stroke. Evidently the electric-spark device is unlimited in its possible adjustment.

Kinds of gas employed for the production of power are natural gas, coal-gas, water-gas, producer-gas, and furnace-gas.

Natural gas is obtained in certain regions by sinking wells. Its composition differs greatly according to locality, but it is almost always rich in hydrocarbons and of high heating power, producing about 900 or 1000 heat units (pound-Fahr.) per cubic foot.

Coal-gas is made by the destructive distillation of bituminous coal, being the same as that originally and still used for illumination. Next to natural gas it possesses the greatest heating value, giving about 700 heat units per cubic foot. Coke, coal-tar, and ammonical liquor are obtained as by-products.

Water-gas is produced by the action of steam upon carbonaceous material at a high temperature. Anthracite or bituminous coal, coke, charcoal, or wood introduced into chambers is ignited and raised to incandescence by blowing air through it, the air being then shut off and steam forced through the mass. At or above a red heat the carbon of the fuel decomposes steam, producing hydrogen and carbon monoxide, the reaction being $C + H_2O = H_2 + CO$. Theoretically the resulting gas would consist simply of equal volumes of hydrogen and carbon monoxide, but practically small quantities of marsh-gas, carbon dioxide, nitrogen, and water vapor are also present, amounting to about 10 per cent. The flow of air and the flow of steam are alternately maintained, the former raising the temperature and

the latter lowering it. The gas thus obtained burns with a blue flame, giving little light, and must be enriched with hydrocarbons to make it suitable for illumination. For power or fuel purposes, however, it has a value nearly half that of coal-gas or about twice that of producer-gas, and does not require the addition of hydrocarbons.

Producer-gas as made in the original Siemens producer is the result of the partial combustion of coal or other fuel by air. Its heating power depends upon the carbon monoxide, hydrogen, and hydrocarbon contained, but these are much diluted by nitrogen from the air and by carbon dioxide due to complete combustion. The later forms of producer employ a jet of steam, which with the coal forms carbon monoxide and hydrogen, also acting to force air through the fuel. Hence it is a combination of the water-gas apparatus with the Siemens producer, and has the advantage over the former of continuous action. A producer of this kind consists of a brickwork chamber, as represented in Fig. 63, into which coal is fed by hand or automatically through a hopper at the top. Sufficient fuel is introduced to form a mass 2½ to 3 feet deep for anthracite and 3½ to 4½ feet deep for bituminous coal. Under this is a bed of ashes almost as thick, in order that the coal may be completely burned before it is dropped below, and to avoid too high a temperature in the lower part of the producer, where the air is introduced. The Taylor gas-producer here represented is provided with a circular iron plate upon which the fuel rests, that is revolved occasionally by hand with a crank and gearing, the object being to prevent the formation of channels in the fuel, and to discharge the ashes at the periphery. The small boiler (Fig. 63*a*) is to supply steam that is decomposed, and also forces air through the mass, as already stated. The gas from the producer passes through cast-iron tubes contained in the economizer, thus transferring its heat to the air which flows around these tubes on the way to the producer. The gas then enters the scrubber filled with coke that is sprayed with water to remove tar, sulphur, and ammonia. This operation is completed in the purifier and the gas enters the holder.

In the Loomis-Pettibone gas-plant the mass of fuel, about 8 feet deep, rests upon a grate. The draft is downward, being produced by a positive exhauster, and the resulting producer-gas

is stored in a holder. When the fuel becomes incandescent the air is shut off and steam forced through the mass, producing

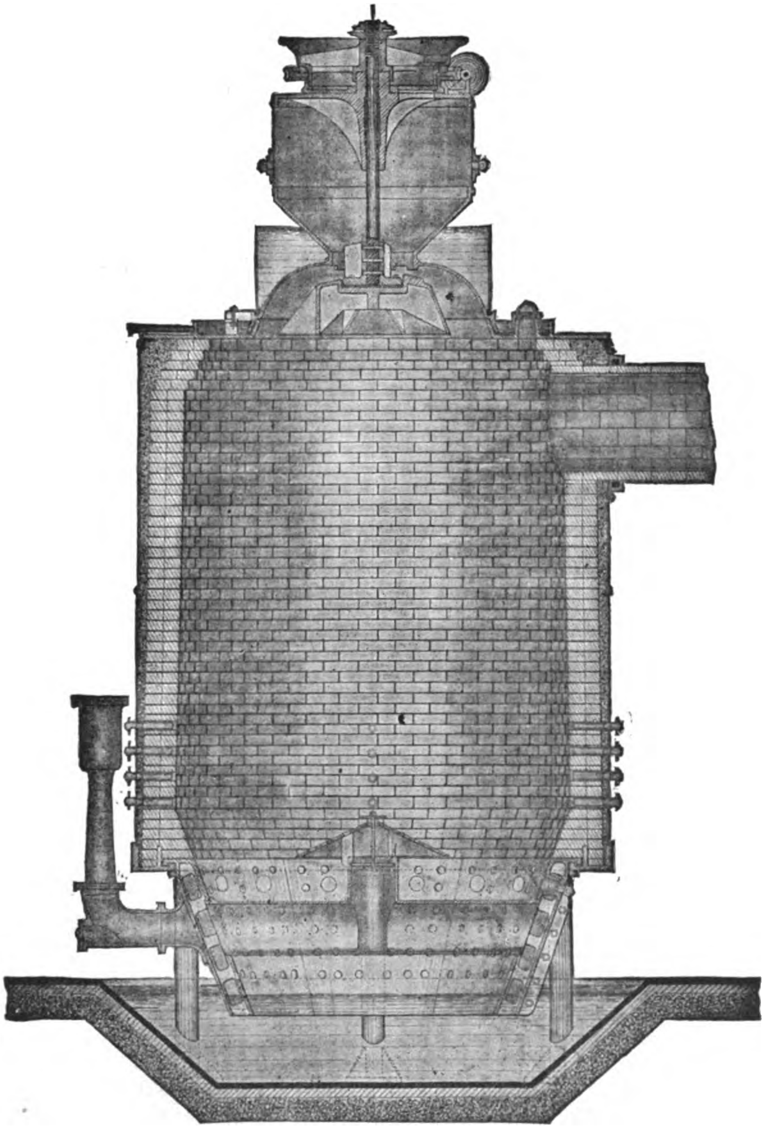


Fig. 63. Taylor Gas-Producer.

water-gas that is carried to another holder, these operations being performed alternately in periods of about five minutes.

The two kinds of gas may be used separately or mixed. In passing downward through the highly heated fuel the gas is freed

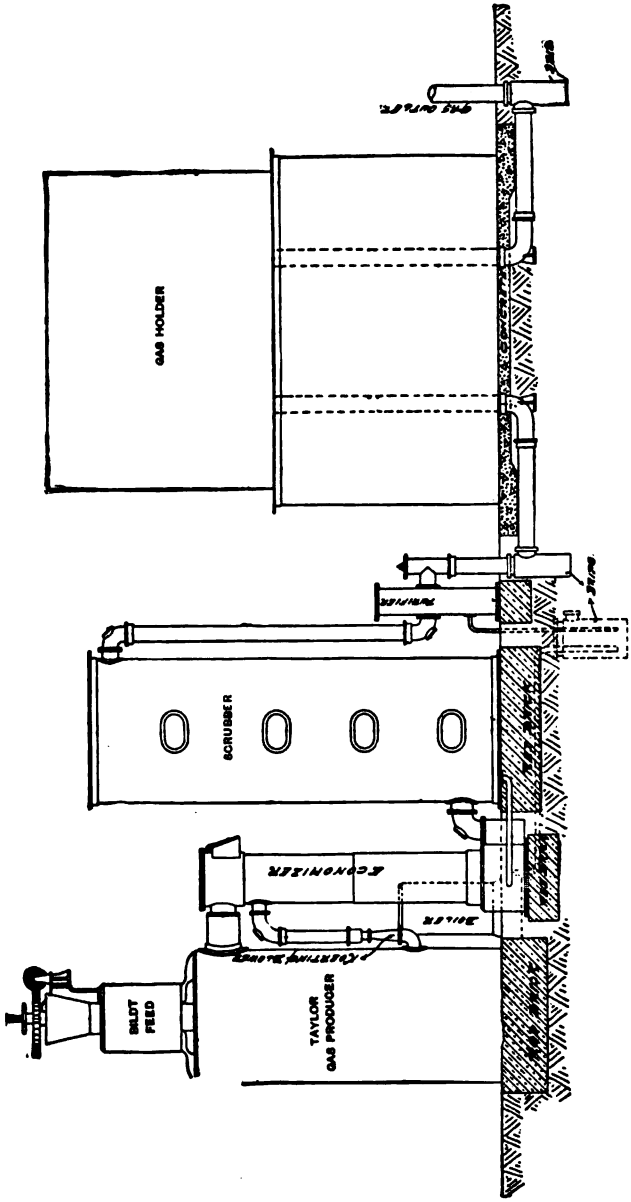


Fig. 63a. Gas-Generating Plant.

from tar. The hot gas from the producers is carried through a vertical boiler which supplies the steam required. A modification

of this plant for 5 to 50 H.P. operates by suction, the flow of gas being produced by the engine which draws in its supply. A blower worked by hand is used in starting, but a holder is not required, the gas being used as fast as it is generated.

Producer-gas consists of nitrogen, carbon monoxide, hydrogen, and small quantities of carbon dioxide and hydrocarbons. The reaction may be represented theoretically as follows:

$$3C + H_2O + O_2 + 4N_2 = 3CO + H_2 + 4N_2;$$

practically as follows:

$$8C + 3H_2O + 3O_2 + 4N_2 = 7CO + 3H_2 + 4N_2 + CO_2.$$

Practically 2 to 5 per cent of carbon dioxide is formed, hence the proportion of carbon monoxide is somewhat less and that of nitrogen more than the equation indicates. Either anthracite or bituminous coal may be gasified in a producer, the latter giving the richer gas, but analyses do not show much difference in composition, because the heavy hydrocarbons are condensed before the analysis, but not in actual use.

One pound of anthracite (85 per cent carbon, 5 hydrocarbon, and 10 ash) makes 80 to 90 cu. ft. of producer-gas retaining about 80 per cent of the original energy in the fuel and having the composition and heating power given in the table on page 212.

Blast-Furnace Gas.—In order to maintain the reducing action in a blast-furnace less than one-third of the carbon can be allowed to become carbon dioxide, hence the discharged gas consists largely of carbon monoxide and is capable of giving 90 to 115 B.T.U. per cu. ft. In the production of a ton of pig iron about 130,000 cu. ft. of this gas are given off and 80 to 120 cu. ft. are required by a gas-engine per H.P.-hour. An ordinary furnace yields about 25 tons of pig iron per hour, hence the gas from it would give $25 \times 130{,}000 \div 100 = 32{,}500$ H.P. as a by-product.

From 10 to 25 per cent of the gas is used for heating the blast, leaving 25,000 to 29,000 H.P., of which 30 to 40 per cent is needed in the blowing-engines. Hence 15,000 to 20,000 H.P. is available for other purposes from each furnace in operation. The usual composition of blast-furnace gas (by volume) is: carbon monoxide 24 to 30 per cent, carbon dioxide 9 to 12 per cent, nitrogen 58 to 60 per cent, hydrogen and hydrocarbons 3 to 5 per cent.

For the other gases the following figures may be taken:

AVERAGE COMPOSITION OF GASES, BY VOLUME.

	Natural Gas.	Coal-gas.	Water-gas.	Producer-gas.	
				Anthracite.	Bitumen.
Carbon monoxide (CO)........	0.50	6.0	45.0	27.0	27.0
Hydrogen (H)...............	2.18	46.0	45.0	12.0	12.0
Marsh-gas (methane, CH_4)....	92.6	40.0	2.0	1.2	2.5
Olefiant gas (ethylene, C_2H_4)..	0.31	4.0	....	....	0.4
Carbon dioxide (CO_2).........	0.26	0.5	4.0	2.5	2.5
Nitrogen (N)................	3.61	1.5	2.0	57.0	55.3
Oxygen (O)..................	0.34	0.5	0.5	0.3	0.3
Water vapor (H_2O)...........	....	1.5	1.5	....	....
Pounds in 1000 cubic feet.....	45.6	32.0	45.6	65.6	65.9
B.T.U. in 1000 cubic feet.....	1,000,000	725,000	325,000	140,000	160,000

Oil-Engines.—An internal-combustion engine using kerosene oil differs from the gas-engine proper only in having a device by which the liquid fuel is vaporized. In the case of a volatile liquid a true vapor will be formed by passing air through it or merely over its surface. In order to use a liquid not readily volatile, heat must be applied to produce vaporization. If the vaporizer is too hot, the fuel will be carbonized; if too cold, it will not vaporize; and for any one liquid fuel the range is very small.

Overcoming Unsteadiness of Gas- and Oil-Engines.—Some types of gas-engines, especially those of small size and the half single-acting forms, are likely to be unsteady in speed. In incandescent lighting this is very objectionable, and some means should be employed to overcome the difficulty in such cases. A storage-battery connected in parallel with the generator may be used, or the engine may be run part of the time to charge the battery from which the lamps are fed. These applications of the storage-battery are discussed in Chapter XXI.

A heavy fly-wheel on the gas-engine shaft tends to prevent variation in speed due to intermittent action, and is still more effectual if a fly-wheel is also applied to the generator-shaft, provided a spring or other elastic connection is interposed between

the engine-shaft and the fly-wheel on the generator, to take up the variations in speed (Fig. 75). It is often found in practice that the ordinary belt-connection is sufficient to prevent the variation from being transmitted to the dynamo shaft, provided the latter carries a fly-wheel also. The fly-wheel may consist simply of a heavy flange cast on one side of the pulley. It is desirable in this case to have the belt, which may be an ordinary leather one, a little longer and slightly more slack than usual, in order that its elasticity and variation in sag may be sufficient to take up the impulses. Modern gas-engines run much more steadily than the early forms, so that trouble in this respect is less common, and in many cases they are directly connected to generators like steam-engines.

The Otto Gas-Engine was brought out by Dr. N. A. Otto in 1867. The original form was the Otto-Langen engine, which was very noisy, the piston being thrown upward with considerable violence by the explosion of the gas; and it was superseded by the "Otto silent gas-engine." This type is manufactured by the Gasmotoren-Fabrik Deutz, at Deutz near Cologne, where it originated; and in this country at Philadelphia.

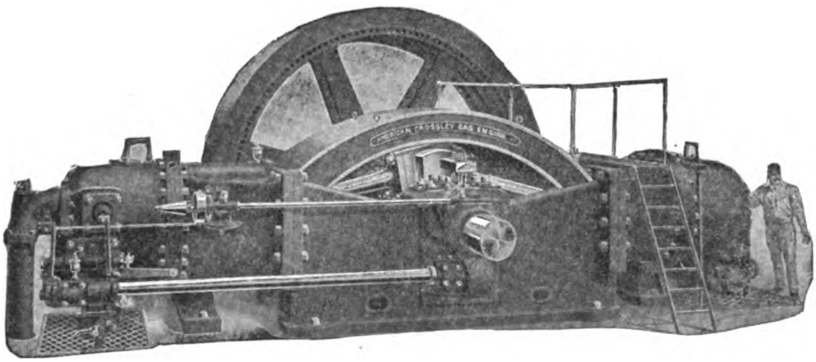


Fig. 64. Crossley Gas-Engine.

The action of these engines as well as that of other types operating on the Otto cycle, such as the Crossley, Westinghouse, and Nash engines, is similar for all and will be described in connection with Fig. 65.

The Crossley Gas-Engine is the Otto type as manufactured in England by Crossley Brothers and in this country in connection with the Loomis-Pettibone gas apparatus already described. In the latter case they are being built in sizes from 50 to 1400 H.P., of the single-, double-, and four-cylinder forms. A double-cylinder American-Crossley engine of 650 brake H.P., illustrated in Fig. 64, is designed for driving an electric generator which is connected directly on the end of the shaft shown in front. The single-cylinder and double-cylinder engines are guaranteed to regulate satisfactorily when driving direct-current generators or 25-cycle alternators in parallel, and the four-cylinder type for 60-cycle alternators in parallel.

The Westinghouse Gas-Engine is built in two-cylinder and three-cylinder types, the former from 10 to 85 H.P. and the latter from 35 H.P. up. A vertical section through one cylinder of the three-cylinder form is shown in Fig. 65, all three being exactly alike. There is a four-cycle operation in each cylinder which is therefore half single-acting, so that a working stroke occurs in every revolution with two cylinders, and for each two-thirds of a revolution with three cylinders.

A shaft *A* carries the exhaust-valve cams and is driven by gearing from the main shaft at one-half the speed of the latter. The exhaust-cam of each cylinder works against a roller at the end of the guide-lever *G*. A long stem *H* projects downward from the exhaust-valve *E* and rests on the end of the lever *G*, the valve being held to its seat by the helical spring as shown. The shaft *A* carries another cam for each cylinder, engaging with a roller on the lever *B* acting through a vertical stem *D* on the lever *C* that actuates the inlet-valve *J*, also closed by a spring. There is also an ignition mechanism which, at the proper instant, breaks an electric circuit, producing a spark at the terminals of the igniter. The upper portions of the cylinders are water-jacketed, as indicated at *PR*. The gas and air enter the mixing valve-chamber by separate inlets, the proportionate amounts being adjustable, and the mixture passes through a distributing-chamber to the port and inlet-valve *J*. In the position indicated the piston is on its downward stroke, the charge being previously ignited at maximum compression. At the end of this working stroke the exhaust-valve *E* opens and the spent

gases are forced out by the upward motion of the piston. A fresh charge is then drawn through the inlet-valve *J* on the down-

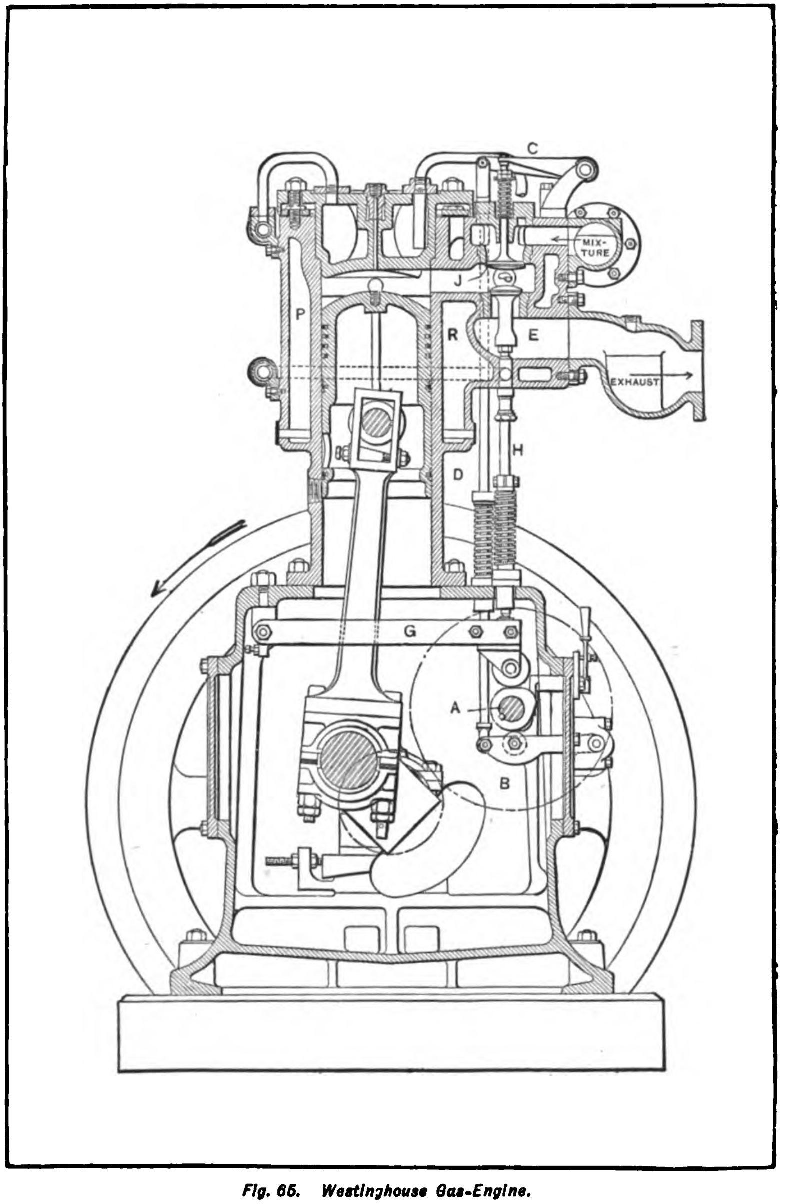


Fig. 65. Westinghouse Gas-Engine.

ward stroke; it is compressed on the upward stroke, after which it is ignited, and so on.

The governor of the Westinghouse gas-engine is of the fly-ball type and controls the areas of the ports through which the gas and air are admitted to the mixing-chamber. This variation of the gas-port area is effected by a cylindrical valve or shell turned by a hand-lever so as to uncover more or less length of port. A separate lever similarly controls the air-port, thus enabling any desired proportion of gas and air to be fixed. The governor merely alters the quantity of the charge, but not the quality of the mixture. Each of the two hand-levers carries a

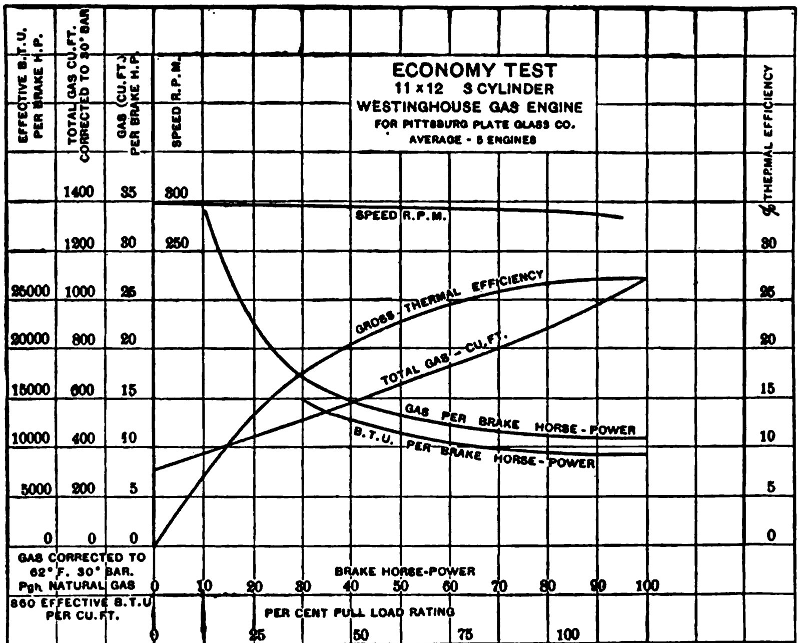


Fig. 66. Tests of Westinghouse Gas-Engine.

pointer moving over a fixed scale, so that they can be set or reset accurately.

Westinghouse gas-engines are started with compressed air supplied by a small compressor that may be operated by hand if necessary, but is ordinarily belt-driven a few minutes a day to charge a storage-tank. One cylinder is temporarily converted into a compressed-air engine by altering the action of the valves, and after three or four revolutions the gas and air are drawn into and exploded in the other cylinder or cylinders; the compressed air is then shut off and the engine runs normally.

Curves showing results obtained from an 80-H.P. Westinghouse gas-engine are given in Fig. 66.

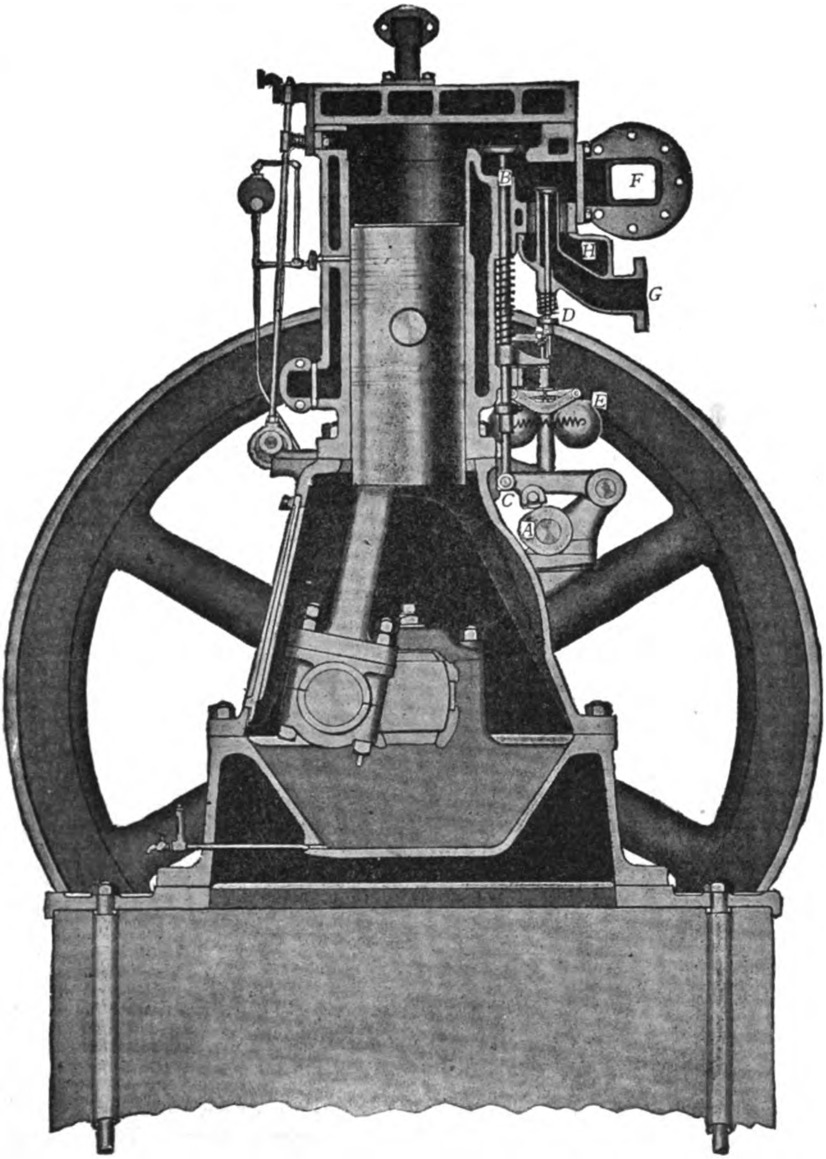


Fig. 67. Cross-Section through Cylinder, Nash Gas-Engine.

The Nash Gas-Engine is an American design and employs two or more vertical cylinders each operating upon the Otto cycle. The

admission-, gas-, and exhaust-valves are all of the poppet type, and are operated through a cam-shaft and lever. Fig. 67 shows a section through one of the engine cylinders and its valve equipment, each cylinder being similarly arranged. *A* is the cam-shaft, *B* the admission-valve, and *C* the lever connected to the valve-stem. The valve action is as follows: If the machine is running at its rated speed, the admission-valve is lifted every fourth stroke, and as it rises its stem engages with a pawl on the stem of the gas-supply valve *D*, and lifts it, thus allowing gas to pass to the mixing-chamber, from which it enters the working cylinder through the opening of the admission-valve. If the engine tends to speed up, the fly-ball governor *E* shifts the pawl, and the gas-valve is not lifted; thus only air is supplied to the working cylinder, and an explosion is missed, this action continuing until normal speed is again reached. The method of ignition employed may be either the hot tube or the electric spark as desired. The exhaust is at *F*, the air-supply at *H*, and the gas-supply through *G*.

The Körting Gas-Engine is of the two-cycle type and secures the proportioning of air and gas by drawing these constituents into two separate cylinders whose volumes have the desired ratio. The pistons of this pair of cylinders are on the same rod and act to displace definite quantities of air and gas into the working cylinder. Hence the latter is not required to draw in the charge and is able to produce an impulse at each revolution, the other stroke being devoted to compression. Two such working cylinders are thus equivalent to the ordinary double-acting steam-cylinder. Governing is effected by varying the time during which the working cylinder is open to the supply cylinders, thereby changing the amount but not the composition of the charge. In the Lackawanna Steel Company's Plant at Buffalo, N. Y., there are eight Körting gas-engines of 1000 H.P. each, and sixteen more of 2000 H.P. each are being installed. Five of these are directly connected to 500-K.W., three-phase, 25-cycle, 440-volt, General Electric alternators, and the other three to 500-K.W., 250-volt, direct-current generators. The power cylinders of these engines are 24¾ inches in diameter with a stroke of 43¼ inches, developing 1000 H.P. at 100 r.p.m.

Mietz and Weiss Gas- and Kerosene-Engines.—This engine,

being of the two-cycle type, has its crank-chamber enclosed and the air-supply is moderately compressed in this space during the working stroke. An eccentric on the main shaft operates a small plunger by means of which the oil is injected into the cylinder. This oil is delivered upon a conical vaporizer preheated by a lamp in starting, but kept hot by the combustion after the engine is running. The air-charge is received from the crank-chamber through a port opened at the end of the impulse-stroke, after the exhaust-port has been opened, through which latter the spent gases escape. A deflector directs the incoming charge toward the head of the cylinder and away from the exhaust-ports. A valve limits the amount of oil injected, and the speed is automatically governed by varying the length of the stroke of the oil-pump. This engine may be converted into a gas-engine by omitting the oil system, and providing a small auxiliary cylinder in which the gas is compressed to the same extent as the air, so that both are forced into the working cylinder and the spent gases expelled.

The following are the most important books relating to the gas-engine.

Gas-Engine Design, Dr. C. F. LUCKE.
The Gas-Engine, F. R. HUTTON.
The Gas- and Oil-Engine, DUGAL CLERK.
Gas- and Petroleum-Engines, B. DUNCAN.
Gas-Engines, F. B. GOVER.
Die Verbrennung-Motoren, GULDNER.
Les Moteurs de Gas, A. WITZ.
Noveaux Moteurs de Gas, S. RICHARD.

CHAPTER XIV.

WATER-WHEELS AND WINDMILLS.

WATER-WHEELS of various forms are, next to the steam-engine, the most important prime movers for driving dynamos. The advantage of water-power is its cheapness; but it has the disadvantages of being rather difficult to regulate perfectly and maintain a constant speed with a variable load, and it is usually very unreliable, being scanty, or failing entirely, during the summer, and being liable to great trouble from ice and floods during the winter and spring. The enormous water-power at Niagara, which is practically constant throughout the year, is absolutely without a parallel; and in practically all other places considerable trouble is caused by excess or deficiency of supply at different seasons. For these reasons the cheapness of water-power is sometimes more apparent than real, and from the inevitable laws of demand and supply its cost becomes nearly equal to that of steam-power when everything is considered. For example, it is often necessary to have an auxiliary steam-plant in case of failure of water-supply or break-down of the plant; hence the interest, depreciation, etc., upon this steam-plant should be included in the total cost of the water-power. When, however, a reliable water-power can be obtained, it usually enables electric current to be generated more cheaply than by steam-power; and there are many places in this country and abroad where this is very successfully accomplished. In fact, the practice seems to be almost universal to utilize, wherever available, a water-power for generating electricity for lighting or power purposes, even if the current has to be transmitted many miles.

Types of water-wheel formerly used were undershot, overshot, and breast wheels, but turbines and tangential or jet wheels are the forms now generally adopted because of their greater efficiency and compactness.

Turbines are very extensively used for driving electric gen-

erators, and possess the advantages of high efficiency,—being 80 to 85 per cent,—economy in space occupied, and close agreement in speed with that of the generator, so that the two can be directly coupled or easily connected by belting or gearing. They may be arranged to revolve either upon a vertical or horizontal axis; and there are also three types, depending upon the direction in which the water flows through the wheel. These are: *parallel-flow* turbines, in which the motion of the water is approximately parallel to the axis of rotation; *outward-flow* turbines, in which the water is supplied at the center, and is discharged in currents radiating from it; and *inward-flow* turbines, in which the water enters at the periphery, and is discharged from the center. Turbines differ from other forms of water-wheel in the fact that all the buckets or blades are acted upon by the water at the same time, instead of only a portion of them, the action being equal and continuous on all sides. This tends to reduce the strains and friction, particularly with outward- and inward-flow turbines in which the pressures are almost entirely balanced in all directions. In the case of parallel-flow wheels the upward thrust can be made to relieve the weight, or two turbines may be combined so that their thrusts counteract each other.

The reason for the high efficiency of the turbine is the fact that the water after passing through the wheel leaves it with a small velocity; or, in other words, almost all of its energy is taken out. In this respect it is similar to the steam-turbine (Chap. XII), but the action is much simpler because no expansion or thermal changes need be considered. Let *BB* in Fig. 68 represent a portion of the fixed guide-blades of a parallel-flow turbine into which the water enters from above, as indicated by the arrow *A*, and strikes against the buckets of the wheel *CC*, causing it to revolve in the direction *EF*. The water is deflected by the curved blades of *CC*, until it flows out of the wheel in the direction *DE*. If the forward velocity of the wheel is *EF*, and the backward velocity of the water relative to the wheel is *DE*, then it is deliv-

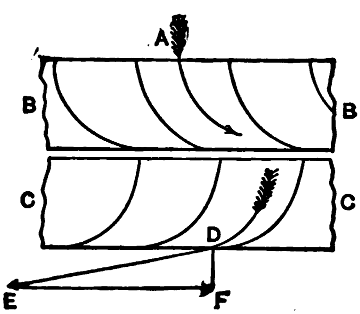


Fig. 68. Principle of the Turbine.

ered with an absolute velocity *DF*, about one-fifth of its original velocity when entering the wheel; thus nearly all of the energy is taken from the water and utilized to drive the turbine. If the wheel were designed to make the angle *DEF* smaller, the velocity *DF* would be still further diminished; but a certain velocity is practically required in order that the water may be delivered and flow away. All other forms of turbine operate on the same principle; in the outward-flow wheel, for example, the water is brought to the center with a full velocity, and, after flowing outward in all directions, is delivered at the periphery with a velocity sufficient only to carry it out of the way of the water that follows it.

The energy in a moving mass is proportional to the square of its velocity, being $\frac{1}{2} mv^2$: therefore, if the water issues from the wheel with only $\frac{1}{5}$ of its initial velocity, it retains only $\frac{1}{25}$ of the initial energy; or, in other words, 96 per cent of the kinetic energy has been taken from it. There are, however, other losses in a water-wheel to be considered. These may all be put in the following form:

$$\frac{WH}{33000} = P + p + \frac{Wh}{33000} + \frac{Wh_1}{33000} + \frac{Wv^2}{66000g}.$$

In this expression W is the weight in pounds of water flowing per minute; H is the total head or fall in feet: hence the first member is the total available H.P. P is the actual brake H.P. developed by the wheel; p is the H.P. lost in friction of bearings; h is the head lost in resistance to the flow of water through the wheel and passages leading to or from it; h_1 is the head lost by the fact that the total fall cannot be utilized, since the wheel is usually placed a certain distance above the lower water-level, but a large portion of this energy is often saved by the use of a draught-tube; v is the absolute velocity in feet per second at which the water issues from the wheel (represented by *DF* in Fig. 68); and g is the acceleration of gravity, equal to 32.2: hence the last term gives the H.P. remaining in the water due to the velocity with which it leaves the wheel.

Tangential Water-Wheels are provided with buckets projecting outward on the periphery, against which a jet of water issuing from a nozzle impinges tangentially (Fig. 72). For this reason

they are also called *jet-wheels*. Frequently they are designated *impulse-wheels*, because the water appears to produce its effect by merely striking against the buckets. In point of fact energy is obtained from the water by deflecting it backward along curved surfaces, the action being equivalent to that of the turbine, as may be seen by comparing Figs. 68 and 72. The chief distinctions between the two types are the facts that tangential wheels have no stationary guide-blades, and only a few buckets are acted upon at one time, usually by a single jet, hence they are sometimes called partial turbines.

Development of a Water-Power.—The dams, raceways, wheel-pits, etc., required to make a natural water-power available for use are so extensive, and vary so greatly in different cases, that it is impossible to more than touch upon them in the present book. For information on this subject, reference may be made to the standard works on mechanical and civil engineering, and to the pamphlets of the various manufacturers of water-wheels.

Measuring the quantity of water that flows in a given time is the first step to be taken. This may be done in the case of small streams by constructing a temporary dam or weir over which the water flows through a rectangular notch, the quantity of water being calculated from "weir tables." In large streams the cross-section may be determined by carefully measuring the depth at a number of points on a line at right angles to the stream. The area thus obtained is multiplied by the mean velocity of the stream to give the volume of flow. The mean velocity is usually about 80 to 83 per cent of the maximum velocity in the middle of the stream, which latter may be found by timing a floating stick. The so-called *miner's inch* for measuring water is the amount that will flow through each square inch of an orifice that is a certain distance below the surface. This depth is usually 6 inches, in which case the quantity is about 1.5 cubic feet per minute, the rate being slightly less for small openings of a few square inches, and slightly more for large ones. On account of its indefiniteness, being rated at from 1.36 to 1.73 cubic feet per minute in different cases, the miner's inch is a very unsatisfactory measure, and should always be replaced by the cubic foot or other definite unit. Measurements of the quantity of water should be made in the dryest season of the year, when the flow is the least,

since the *minimum* amount usually fixes the practical value of a water-power. But in electric lighting it fortunately happens that in July and August, during which months the flow is ordinarily the least, the number of lamps is usually a minimum also; hence the full capacity of the plant may be more than the minimum water-power.

Water-power dams are made in innumerable forms, and of various materials, such as plank, timbers, logs, piles, stone masonry, etc. In most instances they involve a large part of the expense of a water-power plant, and almost every case is a special one, differing more or less from all others. In short, the design and construction of water-power dams constitute an important branch of civil engineering.

A canal, or raceway, is usually constructed to convey the water from the stream above the dam, or fall, to the point where the wheel is located. This should be of sufficient depth so that the water in it shall not flow more than 90 to 120 feet a minute. The mouth of the canal, or head-race, should be parallel with the direction of the stream, in order that ice, logs, and *débris* shall not be carried into it; in fact, it is still better if the opening of the canal, or raceway, faces down the stream at an angle of 10° or 20°, which still further reduces the chance of ice or drift-wood floating into it. The canal, or race, should also be protected by a floating boom of timber extending across the entrance.

A flume, or forebay, built of timbers and planks, masonry or concrete, leads from the canal, or head-race, and conveys the water to the penstock or to the turbine directly. A rack or screen of iron bars and rods should be placed in the flume, or forebay, and inclined backward at an angle to cause the *débris* to be brought to the surface and easily removed, as represented in Figs. 69 and 69*a*.

Wheel-Pit.—The formation of the ground may make it possible to arrange the turbines on the bank of the stream, and simply inclose them in a building or casing. Usually, however, it is necessary to dig a pit, in which the turbines are located.

A penstock made of sheet steel or wood planking conveys the water from the flume, or forebay, to the wheel. In the penstock, which is sometimes vertical, the actual descent of the water takes

place; but, if more convenient, the penstock may be inclined, the effect being due simply to the vertical fall. The turbine is located in, or connected to, the bottom of the penstock. Where the head is not great and it is not necessary to carry the water downward any considerable distance, the turbine is placed in the end of the flume, as shown in Fig. 69*a*, and may be open but usually inclosed in an iron casing. Penstocks made of $\frac{3}{8}$ or $\frac{1}{2}$ inch sheet iron or steel

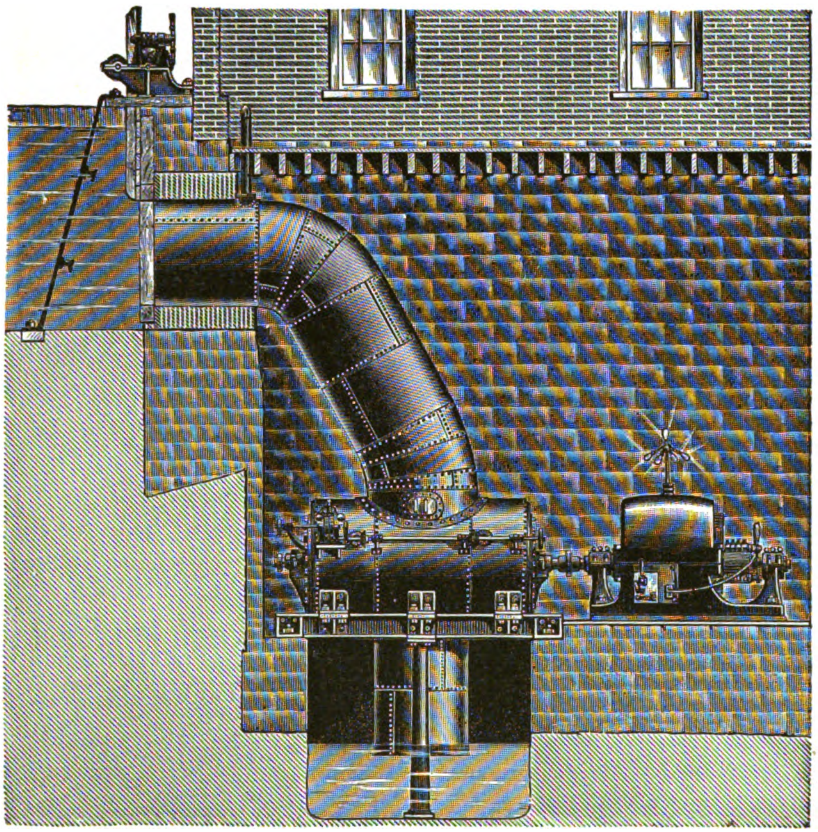


Fig. 69. Pair of McCormick Turbines Directly Connected to Generator.

riveted are usually employed in the best practice, as they have the advantages over planking of compactness and less liability to leakage. The end of the penstock is riveted or bolted directly to the casing of the turbine. A gate should be provided at the entrance to each penstock to control the flow of water; and in cases where it is divided into several branches to supply different wheels, there should be a

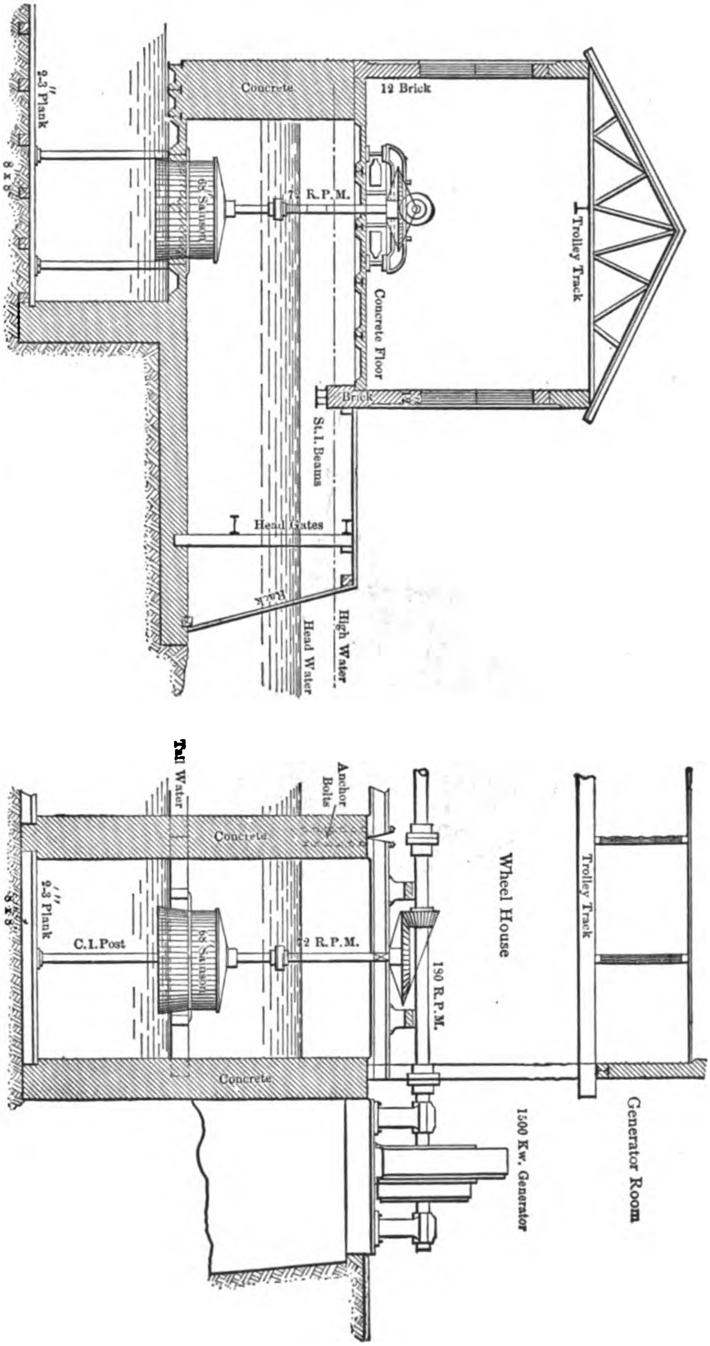
gate in each branch. Racks or screens made of iron bars and rods are also needed at the entrance to the penstock (Fig. 69).

Draught-Tube.—The turbine may be located at the foot of the total fall; in fact, it may actually be placed below the surface of the lower water-level, that is, submerged in the tail-water. It is usually preferable, however, to raise the turbine somewhat, in order to make it more accessible, in which case a draught-tube should be connected to it. This may be of any reasonable length, provided its vertical height is not more than 18 or 20 feet, and still realize the full effect of the total fall of water, since it acts by suction. The draught-tube is usually made of riveted sheet-steel, and must be air-tight and submerged (6 inches or more) in the tail-water at its lower end in order to maintain a partial vacuum. There should be a space below the bottom of the draught-tube at least equal to its own diameter, so that the water may be delivered freely. In the case of a turbine with a horizontal shaft, the use of a draught-tube is practically essential, because the wheel must be raised some distance above the water-level, which also permits the dynamos to be conveniently belted or directly coupled to the turbine-shaft. The arrangement of the penstock and draught-tube is shown in Fig. 69.

A tail-race or tunnel must be constructed to carry away the water, unless the wheels deliver it directly into the stream below the dam or fall. In the case of the 100,000-H.P. plant at Niagara Falls, a tunnel about 20 feet in diameter and 7,000 feet long leads from the bottom of the two wheel-pits, which are 175 feet deep, located about a mile above the Falls, and empties into the river below the Falls. The cross-section of the tail-race or tunnel should be so large that the velocity of the water in it shall not exceed 90 to 120 feet per minute, as in the case of the head-race. In fact, this rule applies generally to all passages leading to or from the wheel, but in short iron pipes 180 feet, and in longer ones 150 feet per minute is allowable.

Some of the most important forms of turbine in general use are the following:—

The Leffel Turbine, manufactured in Springfield, Ohio, one of the standard types, is made in many different forms suitable for various purposes. The ordinary vertical type, shown in Fig. 70, is usually inclosed in a globe casing of cast iron. The water enters this casing through a pipe bolted to the inlet flange, shown in front; it



Figs. 69a and 69b. Cross-Section and Longitudinal Section of Electrical Generating Plant.

then runs from all sides into the turbine, and finally discharges through a draught-tube bolted to the flange at the bottom.

The casing of the Leffel wheel is provided with a removable cover bolted on the top, allowing the wheel to be lifted out of the casing. A large manhole, as well as handhole, on the side, admit of examination, or the removal of any obstruction that may get into the casing. A bridge-tree bolted to the top cap carries an oil-bearing supporting the upper end of the water-wheel shaft, to which latter a clutch-coupling is attached. Stuffing-boxes are

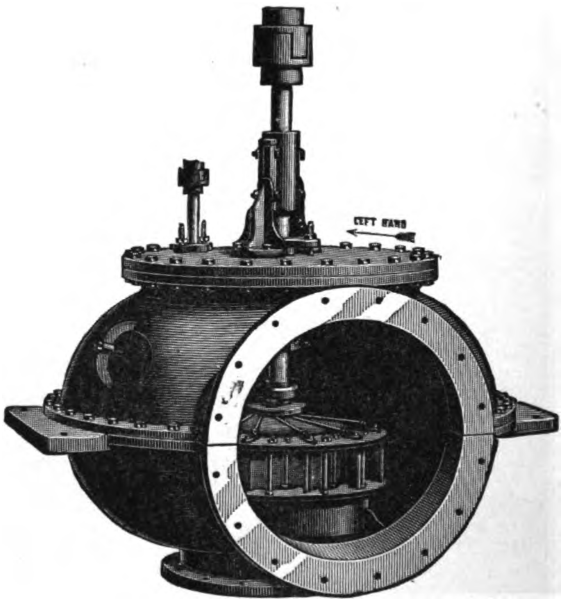


Fig. 70. Leffel Turbine.

arranged in the cap, through which the gate-rod and wheel-shaft pass, preventing leakage of water; and bolts are provided for tightening the packing, should it become loose or worn. The latest design of the Leffel type, called the "Samson" turbine, is made in the simple, vertical form represented in Fig. 69*a*, also several arrangements with horizontal shaft. The Samson wheel is usually provided with a cylindrical casing having cast-iron ends and sheet-steel sides. It is not essential, however, to use the globe or cylinder casing, and in some cases the wheels are set directly in the bottom of a penstock built of planking. The power of Leffel and Samson wheels is controlled by opening and closing the "gates" (i.e., blades),

through which the water enters the wheel all around its periphery. These are pivoted in the middle so as to be balanced and are caused to swing open more or less by the gate-rod, shown on the left of the main shaft in Fig. 70. This gate-rod is operated by hand, or controlled automatically by a centrifugal governor.

The "runner," or moving element of the Leffel and Samson turbines, differs from others in being composed of two wheels of different diameters, one within the other. The water enters the inner wheel or set of buckets through the openings *AB* in Fig. 70*a*,

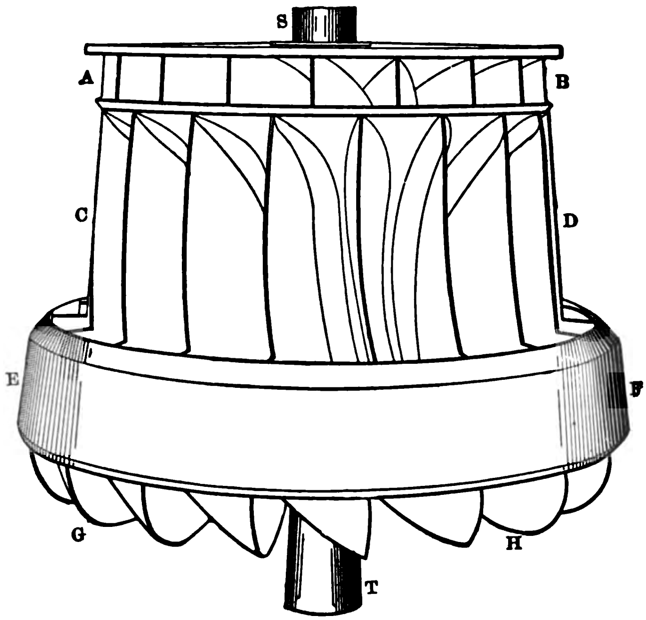


Fig. 70a. Runner of Vertical Samson Turbine.

and it enters the outer buckets through the openings *CD*. Both sets receive water from the same stationary guide-casing within which the runner rotates. The outer or main buckets are made of flanged plate-steel cast into a heavy ring *EF* and a diaphragm separating the two sets of buckets. The earlier Leffel turbine is a combination of the inward or central discharge wheel and of the downward discharge wheel. In the later Samson turbine the discharge from the inner wheel is inward and downward and from the outer buckets it is downward and outward at *GH* in Fig. 70*a*, hence each receives and discharges independently its portion of the water.

The Leffel wheels are made in 7 standard sizes from 10 to 23 inches in diameter, developing with 20-foot head 5 to 50 H.P. at 600 and 450 r.p.m. respectively. There are 12 sizes of Samson wheels from 17 to 68 inches in diameter, 20 to 835 H.P. under a head of 20 feet at 416 to 107 r.p.m. The Samson turbine represented in Fig. 69*a* is 68 inches in diameter and develops 300 H.P. at 72 r.p.m., consuming 20,000 cubic feet of water per minute.

The Victor Turbine is another well-known type manufactured by the Stilwell-Bierce and Smith-Vaille Company of Dayton, Ohio. It is made with "cylinder-gate" in seventeen sizes from 12 to 60 inches diameter, with "register-gate" in four sizes from 6 to 12

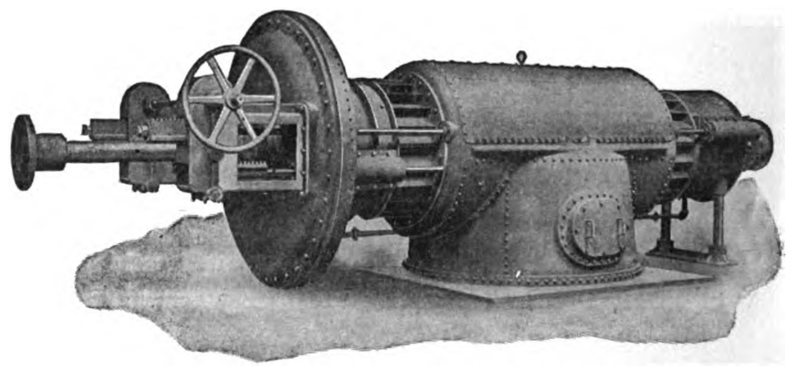


Fig. 71. Pair of Victor Turbines with Central Discharge.

inches diameter, and of the "high-pressure" form in twenty-three sizes from 14 to 72 inches diameter. The last named develops 799 H.P. at 127 r.p.m. under a head of 100 feet, and 8,933 H.P. at 285 r.p.m. under 500 feet head, being capable of operating under heads up to 675 feet or even more. A pair of 27-inch Victor turbines mounted on the same horizontal shaft are shown in Fig. 71. The riveted-steel central discharge casing is designed to be set in an open concrete or masonry flume, the water flowing from all sides into the two sets of openings shown. A large cast-iron ring at the left is built into the flume wall, to which the circular cast-iron flume head is bolted. Through this passes the main shaft with a flanged coupling for direct connection with the generator. A "cylinder-gate" which varies the power by covering more or less of the wheel is moved longitudinally back and forth by draw-rods also

passing through the flume head and operated by racks and pinions as represented.

Results obtained from a 25-inch Victor turbine under 144 feet head rated at 500 H.P. and 480 r.p.m., directly coupled to a 300-K.W. three-phase generator, are given in Fig. 71*a*. This test was made by W. A. Brakenridge, Resident Engineer of the Niagara Falls Power Company, and shows very high efficiencies above half gate, which gave 280 H.P., being 79 to 84 per cent. At smaller loads

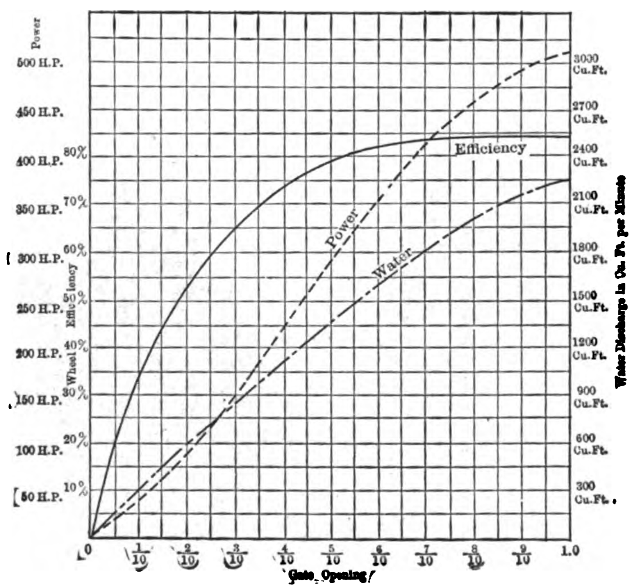


Fig. 71a. Test of 25-inch Victor Turbine under 144 Feet Head.

the efficiency falls rather rapidly, being 65 per cent at 150 H.P. with .3 gate. A wheel may be designed for higher efficiency at light loads, but it would not give more than about 80 per cent at full load. This point should always be considered in selecting machinery of any kind. It is to be noted also that these efficiencies apply to the turbine alone, losses in the generator and in gearing or belting, if used, being excluded. Furthermore there is almost always considerable loss of head in actual operation, the level in the flume being lower and that of the tail-race or wheel-pit being higher than with still water when the nominal head is determined.

The McCormick Turbine is made by the S. Morgan Smith Company of York, Pa., in twenty sizes from 9 to 72 inches diameter,

developing from 12.3 to 1,000.7 H.P. under 20 feet head at 594 and 83 r.p.m. respectively. A pair of 33-inch wheels of this kind developing 1,500 H.P. and directly coupled to a generator are shown in Fig. 69. This arrangement is for central discharge similar to that in Fig. 71, but the two wheels are inclosed in an iron casing to which the water is brought by an inclined penstock, whereas the turbines in Fig. 71 are intended to be submerged in an open flume.

The New American Turbine is manufactured by the Dayton Globe Iron Works in twelve sizes from 16 to 66 inches diameter of the "improved" form, and in seventeen sizes from 13 to 60

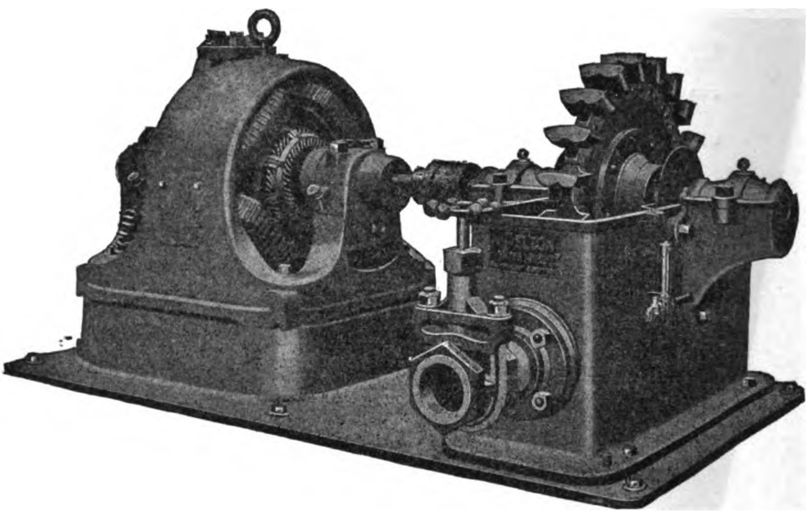


Fig. 72. Pelton Water-Wheel Directly Coupled to Dynamo.

inches diameter of the "special" type. The former are especially designed to drive electric generators, having 33 per cent greater speed and about 20 per cent greater power than the other wheels of the same size. A number of forms adapted to particular conditions are also made, being known as "reduced-discharge" wheels. The runner of the new American turbines resembles that illustrated in Fig. 70*a*, with the upper row of openings *AB* omitted, there being only one set of buckets. It consists of a single iron casting made by means of dry sand cores.

The Pelton Water-Wheel belongs to the class of tangential or jet wheels already defined, and is represented in Fig. 72 directly coupled to a generator. These wheels are particularly adapted

to very high pressures, being used in many cases under a head of 1,000 feet or more.

The great advantage of this type is extreme simplicity and compactness, at the same time giving a high efficiency of 80 to 85 per cent, equal to that of the best turbines. The efficiency of the tangential wheel depends upon a principle similar to that of the turbine, as explained in connection with Fig. 68. A cylindrical jet of water *J* strikes against a bucket *B* having the general form shown in Fig. 73, and is divided into two equal parts by the wedge in the middle of the bucket. Each of these streams *S* and *S* is deflected around by the concave surfaces and delivered backward at a velocity approximately equal to that of the wheel. The streams *SS* should flow out at an angle to the plane of the wheel in order to clear the next bucket at *A* and *E* as shown, otherwise a back pressure would be produced. If *FG* represents the relative velocity of the water and *GH* the peripheral speed of the wheel, then *FH* is the absolute velocity of the water. The angle *FGH* corresponds to *DEF* in Fig. 68.

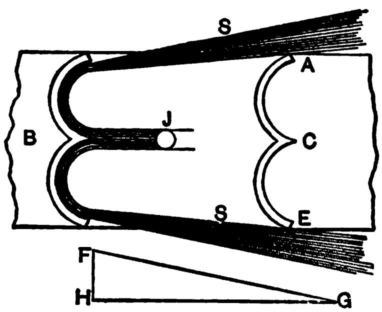


Fig. 73. Principle of Pelton Wheel.

Regulation of Pelton Wheels.—The speed and power of these wheels can be controlled by using several nozzles acting at different points on the periphery, which are turned on or off according to the power required. The power of tangential wheels is also varied by using a *deflecting nozzle* provided with a ball-and-socket joint so that the jet may be thrown either fully or partially against the buckets. This method wastes water and where that is objectionable the regulation may be effected by varying the size of the jet either with a movable, tapering *plug* inserted in the nozzle or by means of a *cut-off hood* on the end of the nozzle, the position of which is altered to adjust the discharge area. Various forms of water-wheel governors described later may be used to secure automatic regulation of speed.

Setting Up and Connecting.—A Pelton wheel is mounted upon a timber frame or an iron base, as represented in Fig. 72, bolted to suitable foundations. To prevent the water from scattering

about, the wheel is inclosed in a housing of wood or iron, with ample clearance on all sides for free discharge. The nozzle should be firmly braced, since the jet produces a strong reaction. Several sizes of nozzle are provided, which can readily be unscrewed and changed to give different power. The water is usually brought to the wheel from the canal or flume by a pipe made of riveted sheet-steel, covered inside and out with asphaltum to prevent corrosion. The pipe, usually made in lengths of about 25 feet for convenient rail or boat transportation, may be connected by a simple *slip-joint*, one end of the pipe being slightly tapered so as to be forced into the larger end of the next section. If properly made this is safe for heads up to 300 feet. The *lead joint*, which will stand 700 feet head, is made with the ends of the pipes of the same size butted together, a sleeve being fitted inside and a collar outside, leaving a space of about $\frac{3}{8}$ inch, into which melted lead is run. A *flanged joint* with a rubber gasket between flanges riveted to the ends of the pipes and bolted together should be used for still higher pressures. Sheet-steel pipe, double-riveted on longitudinal and single-riveted on circular seams, 24 inches in diameter and made of steel .20 inch thick, will safely stand 400 feet head. For other pressures and pipe diameters the thickness of metal should be in direct proportion. The loss of head in pipes due to friction may be calculated by the following expression,

$$F=\frac{L}{1000D}(4V^2+5V-2),$$

in which F is the loss of head in feet, L is the length of pipe in feet, D is the inside diameter of pipe in inches, and V is the velocity of flow in feet per second, usually between 2 and 7, within which limits this formula applies.

Standard diameters of Pelton wheels are 6, 12, 15, 18, and 24 inches, also 3, 4, 5, and 6 feet, the five smaller sizes being called water-motors. Under 500 feet head, producing a pressure of 217 lbs. per square inch and an efflux velocity of 179.3 feet per second, the 6-inch wheel develops 6.7 H.P. at 3426 r.p.m., the 12-inch 15.7 H.P. at 1,713 r.p.m., the 24-inch 83.8 H.P. at 856 r.p.m., the 4-foot 335 H.P. at 428 r.p.m., and the 6-foot 755 H.P. at 285 r.p.m. The approximate power for other sizes of 18 inches or more and heads up to 1,000 feet is given by the expression H.P $=.00188D^2\sqrt{H^3}$, in which D is the diameter and H is the head, both in feet.

The Doble Tangential Wheel differs from the Pelton type in the shape of its buckets; in fact there are many forms on the market. One of the earlier Pelton buckets shown at *E* in Fig. 73*a* is bolted

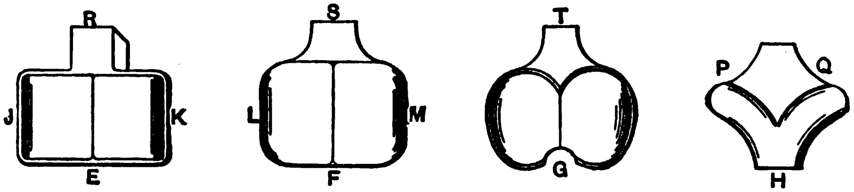


Fig. 73a. Forms of Bucket Tangential Water-Wheels.

to the wheel by the projection *R*. It consists of two half cylinders tangent along the edge *ER*, the ends of the two being flat and perpendicular to the axes of the cylinders. Some of the later Pelton buckets are made with the ends more rounded, but in either case the jet is equally divided by the edge *E* or *F* and discharges largely from the sides *JK* or *LM*. The Doble bucket consists of two half ellipsoids and the outer portion is cut away at *G* where it enters and leaves the jet. The smooth curved surfaces allow the discharge to take place freely in all directions. The bucket of the Hug wheel, on the other hand, discharges at *P* and *Q* or toward the center. Hence there is no settled practice or even general similarity in this respect.

Besides the types of tangential wheels described, the Cazin, Risdon, and Girard are also manufactured, the last being European.

Water-Wheel Governors.—In many factories and mills small variations in speed are not very objectionable, so that it is sufficient to regulate the speed of water-wheels by opening and closing the gates by hand. In electrical plants, however, an automatic governor is usually necessary.

The Lombard Governor consists essentially of a piston working in a hydraulic cylinder, the piston-rod of which terminates in a rack geared positively to the mechanism that opens and closes the water-wheel gate. The admission of water under pressure to one end or the other of the cylinder is determined by a valve, the latter being controlled by a centrifugal governor, shown at the top in Fig. 73*b*. This governor, connected through bevel gearing to a pulley that is driven from the main shaft by a small belt, runs at 485 r.p.m. In the case of tangential wheels or moderate-sized turbines working under considerable head, the pressure of the water obtained from

the flume is sufficient to operate the hydraulic piston. The particular form shown (Type L), with 24-inch stroke and a piston diameter of 6 inches, develops 24.29 ft.-lbs. per foot of head in each stroke. A head of 100 feet giving 2,429 ft.-lbs. would be sufficient to operate a gate of any reasonable size and even smaller cylinders will regulate tangential wheels. Where more work must be done 10- or 16-inch

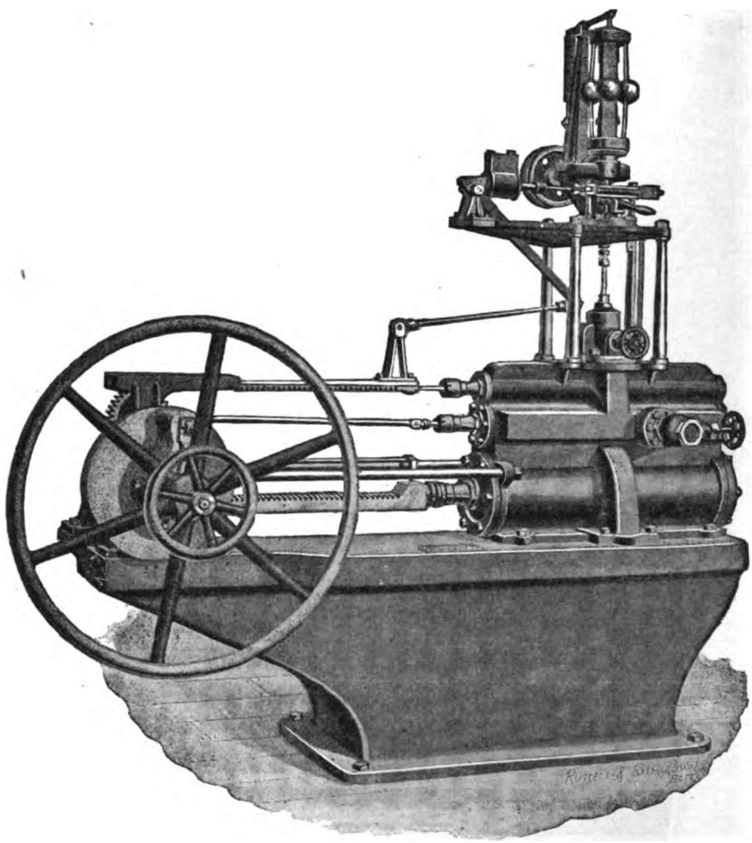


Fig. 73b. Lombard Governor.

cylinders are used, and with insufficient head of water the pistons are operated by oil at a pressure of 200 lbs. per square inch. The oil is supplied from a tank in which air pressure is maintained by a small pump. This last type, with a cylinder 6×24 inches developing 11,300 ft.-lbs. each stroke, is capable of working a large gate, or even several, simultaneously.

In order to synchronize alternators running in parallel, the governors must be controlled, and it is desirable to do this from the switchboard. This is accomplished in the Lombard governor by attaching to it a small electric motor which lengthens or shortens the valve stem, thus varying the speed. The direction of rotation of the motor is determined by two push-buttons on the switchboard, which enables the frequency and phase of the alternators to be regulated exactly. A pin-clutch operated by a small hand wheel also enables the gates to be worked by hand with the large wheel shown in Fig. 73*b*.

The Sturgess Water-Wheel Governor is similar in principle to the Lombard type, the gate mechanism being operated by water or oil pressure acting on a piston and controlled by a valve and centrifugal governor. In this case, however, the piston is rectangular and mounted radially on a shaft whose axis coincides with that of the cylinder. This shaft is connected to the gate by gearing so that the motion of the piston, which swings through 315°, causes it to open or close. This governor may also be equipped with a supplementary electric-motor control similar to the Lombard device.

The Woodward Water-Wheel Governor operates mechanically and differs from the two foregoing forms in which the movement

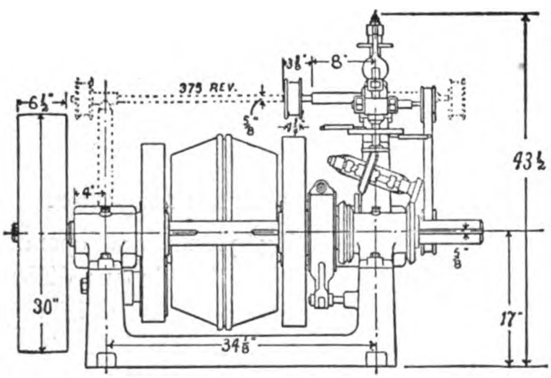


Fig. 73c. Woodward Water-Wheel Governor.

of the gate is effected by water or oil pressure. The power required is taken from the main shaft by a belt to the large pulley in Fig. 73*c*. A double-beveled friction-wheel is keyed to the shaft, to which this pulley is also keyed. On each side of the friction-wheel is a friction-pan carrying a spur-pinion and mounted loosely upon the shaft.

These pinions engage with gears on a back shaft, one directly and the other through an intermediate gear, thus giving reverse movements. A thrust-collar attached to the pulley-shaft enables the friction-wheel to be forced against either friction-pan by means of a fork connected to the mechanism of a centrifugal governor through a lever and crank. Any speed above or below normal causes the gate to close or open since it is connected to the back shaft. The governor is driven by a belt on a small pulley as shown.

Relief Valves.—When the flow of water in a pipe or other closed conduit is suddenly stopped, there is what is commonly called a water-hammer effect. The pressure exerted in pounds per square inch $=MV \div T$, M being the mass (weight $\div 32.2$), V the velocity in feet per second, and T the time in seconds during which the motion is arrested (with uniform retardation). Since the pressure is inversely proportional to this time, it may be enormous if a gate is very suddenly closed, especially at the end of long pipe, when the mass M would be large. To avoid this excessive pressure, which might easily burst the pipe, a stand-pipe or relief-valve should be connected to it near the gate. The former is expensive and clumsy, particularly with high heads, so that relief-valves are more generally used in such cases. They are similar to safety-valves on boilers, being set to open when the pressure rises a certain amount above its normal value.

Connection of Water-Wheels with Generators will be considered in the following chapter, in which direct coupling, belting, and gearing are discussed.

WINDMILLS FOR ELECTRIC LIGHTING.

In some cases electric-lighting plants are operated by the power obtained from windmills; but the obvious difficulty is the unsteadiness of the wind, the slightest variation in voltage being particularly objectionable in incandescent lighting. This difficulty is more or less overcome by the use of a storage-battery, which is charged by the windmill and dynamo, the actual current for lighting being obtained from the battery.

According to the observations of the United States Signal Service,* the average velocity of the wind for the year is 9 miles per hour along the North Atlantic coast and in the Northwestern States,

* "Horse-power of Windmills," *Scientific American*, July 8, 1893.

10 miles on the plains of the West, and 6 miles in the Gulf States. A 10-mile breeze exerts a pressure of about $\frac{1}{2}$ lb. per square foot; 15 miles, $1\frac{1}{10}$ lbs.; 20 miles, 2 lbs.

The apparatus for an electric-lighting plant consists of a windmill of any of the numerous types manufactured and a dynamo having a capacity equivalent to the maximum power of the windmill, the two being mechanically connected by belting or gearing. It is also necessary to apply some automatic device which will cause the dynamo to charge the storage-battery only when its speed and voltage rise above a certain value. This may be mechanical or electrical; for example, a centrifugal governor combined with a switch so as to close the latter when the speed reaches a certain limit and open it when the speed falls below this value; or an electromagnetic device may close the circuit when the voltage of the dynamo rises to the proper point. If such a device were not used, the battery would discharge back through the dynamo when the *E.M.F.* of the latter fell below that of the former.

Another device to maintain reasonably constant voltage with wide variations in speed consists in winding the field-magnets of the dynamo differentially; that is, with a series-coil which opposes the magnetizing effect of the shunt-coil, so that, as the speed of the dynamo and the current increase, this series-coil will tend to demagnetize the field and keep down the *E.M.F.*

For further information in regard to water-power and wind-power, reference may be made to the following books and articles:

A Treatise on Hydraulics, by Prof. M. Merriman; 8th Edit., N. Y., 1903.

Hydraulic Motors and Turbines, by G. R. Bodmer; 3d Edit., N. Y., 1902.

Hydraulics and Hydraulic Motors, by Weisbach. Translated by A. J. DuBois; 2d Edit., N. Y.

Hydraulic Power Engineering, by G. Croyden Marks, London and New York, 1900.

Hydraulic Machinery, by R. C. Blaine, London and New York, 1897.

Development and Transmission of Power, by W. C. Unwin, London, 1894.

Construction of Mill Dams. Published by James Leffel & Co., Springfield, Ohio.

"Central Stations Operated by Water Power," a paper before National Electric Light Association, September, 1891, *Electrical Engineer*, Sept. 16, 1891. (Historical.)

"Cost of Steam Power, etc." (Appendix on Water Power), Dr. C. E. Emery, *Trans. Amer. Inst. Elec. Eng.*, March, 1893.

"Water Power, Its Generation and Transmission," Samuel Webber, *Trans Amer. Soc. Mech. Eng.*, December, 1895.

The Windmill as a Prime Mover, by A. R. Woolf, New York, 1890.

"Generating Electricity by Windmills," I. N. Lewis, *Engineering Magazine*, December, 1894.

CHAPTER XV.

MECHANICAL CONNECTIONS BETWEEN ENGINES AND GENERATORS.

DIRECT DRIVING, BELTING, AND GEARING.

VARIOUS means are employed to connect the engine or other prime mover with the generator, of which the following are the most important:—

1. Direct driving.
2. Belting (flat).
3. Rope driving.
4. Toothed gearing.
5. Peculiar forms of connection, such as friction and magnetic gearing.

Other apparatus, such as shafting, clutches, hangers, pulleys, etc., are used in connection with the above-named methods.

Direct Driving.—This term may be applied generally to all cases where a generator is driven without intermediate belting or gearing. Direct connection may be used specifically to designate the arrangement in which the revolving armature or field is mounted on the engine or turbine shaft; and direct coupling should mean that each has its shaft, the two being coupled together either rigidly or flexibly. These distinctions are desirable, but ordinarily the terms are all used in the same general sense. This method is the simplest, and for that reason the most desirable connection provided it can be carried out without involving sacrifices that offset its advantages. It compels the engine and generator to run at the same speed, and gives rise to certain difficulties, for the reason that the most desirable speeds of the two machines may not agree. The most advantageous speed of a generator is considerably higher than that of the corresponding reciprocating steam- or gas-engine. Hence it is necessary either to raise the speed of the engine above the point at which it works well or reduce the speed of the generator below

that at which it gives its full capacity, in order to make the two coincide. The running of an engine above a certain speed is decidedly objectionable, since it reduces its efficiency, requires more attention, increases the wear and repairs, and consumes more oil.

The speed of a generator, on the other hand, can be brought down without much sacrifice of efficiency or other disadvantage, except that the output is decreased, or, what is the same thing, the size and weight are increased for a given output. The usual way to construct a low-speed dynamo is to make the armature of large diameter, thus securing a sufficiently high peripheral velocity; at the same time the armature core is made in the form of a ring, with comparatively small radial thickness, in order to reduce the weight of iron required. Nevertheless, the frame, shaft, bearings, and other parts of such a machine are necessarily heavier and more costly than if the armature were of smaller diameter and higher speed. The compactness, simplicity, and general advantages of direct coupling are so great, however, that they generally warrant the extra cost. The subject of generator design and construction is discussed in Chapters XVII and XVIII and the various cases of direct driving will now be considered separately.

The direct driving of generators by water-turbines can usually be carried out without departing much from the normal speed of either machine; that is to say, the ordinary speed of a turbine agrees fairly well with the normal speed of a generator of corresponding power provided the head is sufficient. The shaft of the former, however, is usually vertical, while that of the latter is horizontal; hence, in order to drive directly, one or the other must be changed from its ordinary arrangement. This can be done either by constructing a generator to revolve on a vertical shaft or a turbine with a horizontal shaft (Fig. 69) can be obtained. If the armature is mounted directly upon the shaft of a vertical turbine, the total weight becomes large and must be supported on some adequate form of thrust- or step-bearing. In some cases provision is made to take a portion or all of the weight off of the bearings, either by magnetic attraction or by causing the upward pressure of the water in the turbine to balance the weight. Devices of the former kind have been constructed by the Oerlikon Works of Switzerland, one of which, described in the *Electrical Engineer* (New York) of Aug. 22, 1894, balances a load of 30,000 lbs., consisting of a 600 H.P. turbine

and dynamo, the consumption of electrical energy being only $\frac{1}{3}$ H.P. per ton, or $\frac{1}{6}$ of 1 per cent. The magnet, which is fixed, is circular in form and multipolar. It acts upon a flat ring armature attached to the shaft, and made of iron ribbon to prevent the generation of eddy currents. Provision is made for varying the attracting force. The upward pressure of the water has also been used to balance the weight, but the serious difficulty arises that this pressure varies with the amount of opening of the gate and is therefore insufficient at light loads. In the case of the 5,000 H.P. two-phase generators of the Niagara Falls Power Company, the revolving field-magnet is mounted on the top of the vertical shaft of a turbine. The weight of moving parts is about 150,000 lbs. and is carried on a single flange attached to the shaft that revolves on a fixed ring, oil under high pressure being forced between the two surfaces so that the weight practically floats upon it. The principle is the same as that of the step-bearing of the Curtis steam-turbine represented in Fig. 60.

A turbine with horizontal shaft can be coupled directly to a generator in the manner illustrated in Fig. 69. This arrangement is open to the objection that the electrical machinery must be placed below the upper water level and rather near the lower level even when a draught-tube is used. Hence it is exposed to moisture to which it is vulnerable or may actually be flooded in case the tail water backs up, as it often does. Nevertheless this plan is frequently adopted on account of its simplicity and its convenience if moisture is properly guarded against. To make any kind of direct driving advantageous it is generally necessary that a considerable head of 30 to 50 feet or more be available. Otherwise the speed of the wheel is so low that a corresponding generator would be unduly expensive. Furthermore the power of a single wheel of reasonable diameter is not sufficient to run a generator of the large size usually desired. For these reasons the arrangement represented in Figs. 69*a* and 69*b* is commonly adopted for low heads, several wheels being used to give enough power for one generator and bevel gearing introduced to multiply the speed as well as to change the direction of motion. When generators are driven by Pelton or other forms of tangential water-wheels, it is almost universal practice to couple them together as illustrated in Fig 72. In many cases each machine is complete in itself and the two are placed on a cast-iron bed-plate. Sometimes one of the four bearings is omitted, requiring the arma-

ture to be rigidly mounted upon or connected to the shaft. Rigid couplings are often used for direct coupling, or flexible couplings similar to that shown in Fig. 75 may be employed with four bearings. In practically all cases the head is sufficient to give the requisite speed and power with a single tangential wheel.

The direct driving of a generator by a steam- or gas-engine is accomplished in several ways, the simplest of which consists in mounting the armature of the generator on one end of the engine-shaft. For example, in Fig. 43 the pulley on the farther side of a center-crank engine may be replaced by the armature, in which case there are only two bearings. Very often another bearing is applied outside

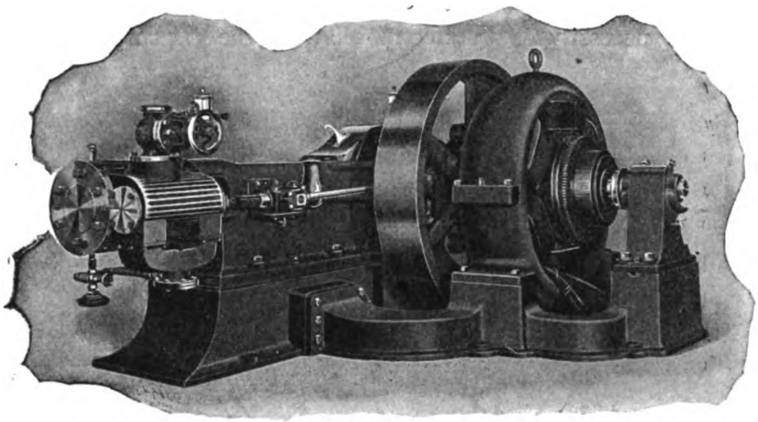


Fig. 74. The Harrisburg Standard Engine Directly Connected to Generator.

of the armature, producing what is known as the three-bearing arrangement, also with center crank. In other cases the armature is mounted alongside of the governor-wheel, as illustrated in Fig. 74, only two bearings being required, and the engine of the side-crank type.

For large engines which are usually cross-compound tne general construction represented on pages 157 and 179 is often adopted, the armature as well as the fly-wheel being mounted on the shaft between the housings of the high- and low-pressure cylinders. In other instances the armature is mounted on one of the shafts, even in the largest sizes, as shown on pages 48 and 49. For smaller sizes of direct-connected units from 25 to 200 K.W. the standardization recommended by the American Society of Mechanical Engineers has already been given on page 178.

Direct coupling comprises an engine and a generator, each complete in itself, and each having two bearings, coupled together by some mechanical connection, which may be either rigid or slightly elastic or adjustable. In the first case, the two shafts are practically equivalent to a single shaft; in fact, they might be made in that form, but it would be very inconvenient in replacing or repairing either the engine or the generator, whereas the mere connecting of entirely distinct machines affords great advantages in this respect. It is somewhat difficult to adjust three or four bearings exactly in line; nevertheless it can be accomplished with care and good workmanship.

The interposition of a coupling having more or less flexibility avoids the necessity for perfectly aligning the bearings of both

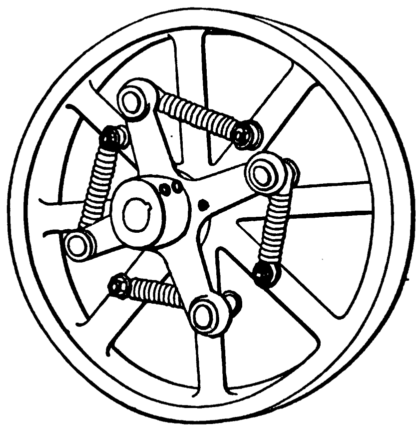


Fig. 75. Flexible Coupling.

machines, and also the serious difficulties which arise if any of the bearings settle or wear more than the others. There are numerous forms of such flexible or adjustable couplings, one of which, that would allow for very imperfect alignment of the two shafts, is represented in Fig. 75, and consists of a wheel and a spider, one rigidly mounted on each shaft. Both are provided with pins, which are connected by springs. Besides taking care of differences in alignment, a flexible coupling tends to reduce fluctuations in angular velocity due to gas- or steam-engines, especially if the armature is heavy or has a fly-wheel attached.

An ordinary friction-clutch or a magnetic clutch (Figs. 79 and

80) is a convenient means for directly coupling an engine and generator. It is easily applied, being especially designed to connect two shafts together, and has the advantage over almost any other coupling of being readily disconnected, so that one or more generators can be stopped without interfering with the engines. These forms of clutch will be described later in the present chapter.

Direct driving with steam-turbines has already been considered—the de Laval arrangement having been shown and described on page 185, the armature being mounted upon the prolongation of the shaft J of the Parsons turbine on page 188, and the Curtis construction having beeu illustrated on page 192.

BELTING.

If the generator is not directly driven by the engine or source of power, it is usually connected by some form of belting. In fact, belting was almost universally employed until about 1892. The simplicity, compactness, and positive action of direct driving have caused it to become the approved method, and belting has become unpopular. Nevertheless, belting is still utilized in a number of instances, more often for smaller machines but in some cases for large ones. One reason for the continued use of belt-driven generators is the fact that they can be applied to second-hand engines or those already on hand that were not designed for direct driving. Greater flexibility in the original design of a plant is possible and new arrangements of old apparatus can be made at any time. The advantages of belting in general are:—

1. It gives almost any desired ratio of speed simply and conveniently.
2. It is cheap itself and on account of higher speed enables a cheaper generator to be used.
3. It is applicable to almost any case provided the space is sufficient.
4. The machines are almost entirely independent, so that either can be changed, repaired, or operated without interfering with the other.
5. The generator is insulated so far as the belting is concerned.

The general disadvantages of belting are:—

1. It requires considerable space, since the machines must be placed a certain distance apart in order to make the belt work properly.
2. The action is not positive, there being a certain slip even in normal working, and with over load or other trouble the belt may run off or break.
3. Belting is somewhat unsteady in action and likely to cause slight fluctuations in the speed and voltage of generators on account of its slipping or flapping. This

is objectionable, particularly in incandescent lighting; but it can usually be avoided by proper design.

4. Belting produces a certain amount of noise which might be objectionable in some cases, and would be a reason for the adoption of direct driving.

5. Belts exert a side pull on the bearings which produces loss of power by friction, also wear. However, there are many generators that have been running for years without showing any considerable wear from this cause.

The following table shows the principal kinds of belting that may be employed, a description of each being given afterwards.

KINDS OF BELTING.

1. LEATHER (flat)	Plain, Perforated.
2. ROPE........	Hemp, Cotton, Rawhide.

Other kinds of belting have been used, such as rubber, cotton, cotton-leather, leather-link, etc., being substitutes for plain leather.

Plain Leather Belting is generally the most reliable and satisfactory. There are three standard thicknesses—single, light-double, and double. For driving generators or other high-speed machinery, "light-double" belting is usually best.

The amount of power that a given belt is capable of transmitting is a matter that is not very definite. The ordinary rule is that a "single" belt will transmit 1 horse-power for each inch in width at a speed of 1,000 feet per minute. If the speed be greater or less, the power is correspondingly increased or decreased.

This rule is based upon the condition that the belt is in contact with the pulley around one-half of its circumference, or 180°, which is usually the case. If the arc of contact is less than half a circle, the power transmitted is less in the following proportion: An arc of contact of 135°, or three-eighths of the whole circumference, gives .84, while 90° gives only .64 of the power derived from a belt-contact of 180°.

If, on the other hand, the upper side of the belt sags downward, and the belt is in contact with more than half of the circumference of the pulley, then the grip is increased, and more power can be transmitted. These facts make it very desirable to have the *loose side of the belt on top*. If the loose side is below, it sags away from the pulleys, and is likely to strike the floor.

The expression for determining the width of a single belt required to transmit a given horse-power is

$$W=\frac{\text{H.P.}\times 1000}{C\times S},$$

in which W is the width in inches, H.P. the horse-power to be transmitted, C a factor depending upon the arc of contact, S the speed of the belt in feet per minute, which is equal to the circumference in feet of the driving pulley multiplied by the r.p.m. Belts slip or "creep" on the pulley about 2 per cent; hence the proper size of pulley should give a calculated belt speed 2 per cent too high.

"Double" belting is expected to transmit one and one-half, and "light-double" one and one-quarter, times as much power as "single" belting of the same width. Belting formulas are only approximate, and should not be applied too rigidly, since the grip of the belt upon the pulley varies considerably under different conditions of tension, length of service, moisture in the atmosphere, etc.

The smooth side of a belt should always be run against the pulley, as it transmits more power and is more durable. The common idea that the rough side of a belt "has more friction" is entirely erroneous.

Generator or other high-speed belts should be made "endless" for permanent work; but may be used with laced joints temporarily. It is best to order an endless belt of the right length from the manufacturer; but if necessary it may be spliced with ordinary skill. Both ends of the belt are pared down on one side (opposite) with a sharp knife into the form of a long, thin wedge, so that when laid together a long uniform joint is obtained of the same thickness as the belt itself. The parts are then firmly joined by cement and often with rivets also. It may be necessary to splice or lace a belt while in position on the pulleys, and for that purpose some form of belt-clamp (Fig. 76) should be employed.

If a belt is ordered to be made endless, or is spliced away from the pulleys, great care should be exercised in measuring the exact length required. The best way to avoid a mistake is to use string that will not stretch, or preferably a wire put around the pulleys in the position to be occupied by the belt. In measuring for a belt, the generator should be moved on its sliding base so as to make the

distance the shortest, in order to allow for the stretch of the belt, which usually amounts to from $\frac{1}{4}$ to $\frac{1}{2}$ inch per foot of total length.

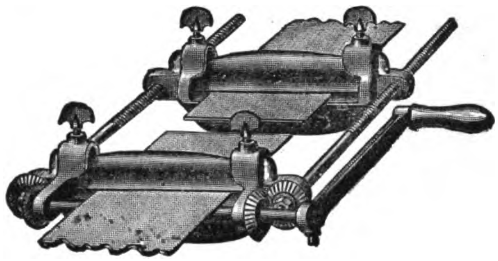


Fig. 76. Belt Clamp.

The lacing of a belt is a simple and common method of making a joint. At high speeds, however, a laced joint is apt to pound on the pulleys, producing noise, and in the case of incandescent lamps it causes flickering; nevertheless, its simplicity and reliability make it allowable in an emergency or for temporary use.

In lacing belts the ends should be cut perfectly square, and there should be as many stitches of the lacer slanting to the left as there are to the right; otherwise the ends of the belt will shift sideways, owing to the unequal strain, and the projecting corners may catch the clothing of persons. There are various methods of lacing, one of which is shown in Fig. 77. In this case two rows of holes are

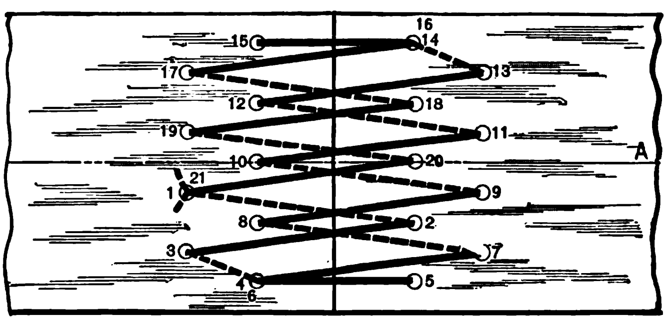


Fig. 77. Method of Lacing Belts.

made with a punch in each end. The nearest hole should be $\frac{3}{4}$ inch from the side, and the first row $\frac{7}{8}$ inch from the end, and the second row $1\frac{3}{4}$ inch from the end of the belt. In large belts these distances should be a little greater. A regular belt-lacing (a strong, pliable strip of leather) should be used, beginning at hole No. 1 and passing consecutively through all the holes as numbered. Very often, par-

ticularly for smaller sizes, only a single row of holes is made in each end of a belt.

Perforated belts are often used for the reason that a film of air is likely to be imprisoned between the belt and the pulley preventing a good grip. Hence small perforations are sometimes made in the belt, especially for high-speed operation (above 2,500 feet per minute), to allow the air to escape; and since these are in the form of narrow slits, with their longest dimension in the direction of the length of the belt, they do not materially reduce its strength.

Arrangement and Care of Belting.—It is very desirable, for satisfactory running, that belts should be reasonably long and nearly horizontal. If it is absolutely necessary to connect pulleys at different levels, the belt should be as nearly horizontal as possible, and should make an angle of at least 45° with the vertical, if possible; otherwise it will not be likely to work well for more than a few horsepower. The distance between the centers of two belt-connected pulleys should be at least 3 times the diameter of the larger pulley. The belt should be just tight enough to avoid slipping, without straining the shaft or bearings. A new belt will not carry as much power as one that has been properly used for a few months.

The generator shaft and the shaft to which it is to be belted must be placed perfectly parallel, and the centers of the two pulleys must be exactly opposite to each other. The machine should then be turned slowly with the belt on, to see if the latter tends to run to one side of the pulley, which would show that the machine is not yet properly "lined up;" and in this case it should be slightly moved until the belt runs properly.

Belts should be as pliable as possible; hence the occasional use of some good belt-dressing is recommended, especially as it permits the belt to be run with less tension. Rosin is sometimes applied to increase the adhesion; but this is a practice allowable only in an emergency, as it may destroy the belt surface. In places where they are likely to catch in the clothing of any person, belts should be inclosed by a casing or railing.

ROPE-DRIVING.

The rope runs in V-shaped grooves in the peripheries of the pulleys, and in some cases this means of driving is preferable to any other.

The advantages of rope-driving are:—

1. It is cheap.
2. More power can be transmitted with a given diameter and width of pulley, on account of the increased grip in the V grooves.
3. It is almost noiseless.
4. Ropes can be used by reason of their lightness to transmit power over greater distances than with any other form of belting.
5. Rope belting can also be employed for very short distances because of the wedging action in the grooves.

The first of the above advantages—cheapness of the rope itself—is offset by the fact that grooved pulleys cost more than those for a flat belt, hence the total cost is about the same.

Manila rope is generally preferred for transmitting power, but cotton, rawhide, and wire ropes are also used. The first has an ultimate strength of 7,000 to 12,000 lbs. per square inch of cross-section, but this is not important, since a driving-rope transmits only 3 to 5 per cent of its tensile strength. Durability is the chief point, since rope belts are rather likely to break owing to internal wear between the fibers and failure of the splice.

The diameter of a single rope necessary to transmit a required H.P. is given by the following formula:—

$$D = \frac{825 \text{ H.P.}}{V\left(200 - \frac{V^2}{1,072}\right)},$$

in which H.P. is horse-power transmitted, V is velocity of rope in feet per second, and D is its diameter in inches.

The maximum power is obtained in rope-driving at a speed of 80 or 90 feet per second. With higher velocities the centrifugal force becomes so great that the power decreases rapidly, and at 140 or 150 feet per second it counteracts the whole allowable tension (usually about 200 D^2 lbs.) and no power is transmitted.

Arrangement of Rope-Driving.—There are two methods of arranging rope transmission: one consists in using several separate belts, and the other employs a single endless rope which passes spirally around the pulleys several times and is brought back to the first groove by a slanting idle pulley, the latter being called the "wound" system. The separate ropes do not require the carrying-over pulley, and if one rope breaks those remaining are sufficient to transmit the power temporarily, whereas an accident with the single-rope arrangement entirely interrupts the service. The carrying-over

pulley is often mounted in bearings which can be moved by a screw or weight so that it can be used as a belt-tightener; but since belt-driven generators are almost always mounted upon sliding bases, this advantage is not of so much value as in the case of other kinds of machinery. The difficulty with separate ropes is the necessity for making several splices, and the fact that it is practically impossible to make and maintain the belts of exactly equal length; consequently they are of unequal tension, and hang at different heights on the slack side, producing an awkward appearance, even if it causes little difference in actual working. The single rope is often supposed to have a perfectly uniform tension in all parts; but it is evident that if there is the slightest slip, the rope will be tighter in the first groove than it will be in the last: this variation is regular, however, and is less unsightly than the very uneven sag of separate ropes.

Shafting.—An intermediate or counter-shaft is undesirable, since it increases the complication and friction losses; but it is used in some electrical plants, especially old ones, either to obtain a greater multiplication of speed than is possible by belting directly or to enable a single engine to drive a number of generators; as, for example, in arc-lighting stations.

The two important kinds of shafting are "cold-rolled" and "turned." The former is rolled to the exact size and requires no further treatment. It has the advantage of a smooth, hard surface, but is difficult to make perfectly true and straight; and if any portion of the surface is removed to make a key-way, for example, it is apt to cause the shaft to bend, owing to unequal internal stresses. Turned-steel shafting is most commonly employed, and has the advantage that shoulders, journals, or other variations in size can easily be made in it. The following table gives the ordinary data of shafting:—

SHAFTING.

Diameter in Inches.	Weight. Lbs. per Ft.	H.P. at 100 Turns per Minute.	Average Net Price per Ft.	Width of Key-seat in Inches.
$1\frac{7}{16}$	5.5	4.3	$0.25	$\frac{3}{8}$
$1\frac{15}{16}$	10.	10.	.35	$\frac{1}{2}$
$2\frac{7}{16}$	15.8	20.	.50	$\frac{3}{4}$
$2\frac{15}{16}$	23.	34.	.70	$\frac{3}{4}$
$3\frac{7}{16}$	31.5	54.	.95	$\frac{7}{8}$
$3\frac{15}{16}$	41.	80.	1.30	1
$4\frac{7}{8}$	62.8	156.	2.00	1
$5\frac{7}{8}$	91.1	270.	4.00	1

The allowable H.P. that the shaft will transmit is given in the table at 100 r.p.m.; for any other speed the power varies in proportion; that is, at 200 r.p.m. it would be twice as great. It is not convenient to make or use shafting in greater lengths than 25 feet for sizes from about $1\frac{7}{16}$ to $3\frac{7}{16}$ inches diameter; for larger or smaller sizes it is desirable to have the lengths still less. They are connected by some of the following forms of coupling.

Shaft Couplings.—There are two classes of these devices—rigid and detachable. The ordinary rigid coupling is the flange type shown at *M* in Fig. 57, which should be secured to the two shafts by tapered keys. The plain sleeve coupling consists of a tube in which the ends of the shafts are held by set-screws or keys, but this form is not so easily disconnected or removed. The clamp or compression couplings, of which there are many forms, simply grip the shafts by screw pressure. They possess the advantages of being easily put on or taken off, and do not require holes or slots to be cut in the shaft.

The simplest form of detachable coupling is the jaw or "grab" clutch represented in Fig. 78. It consists of a jaw which slides

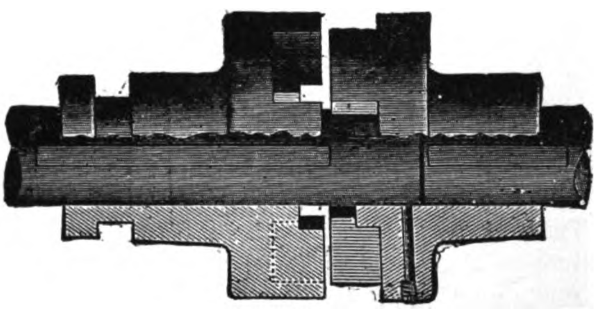


Fig. 78. Jaw Clutch.

lengthwise on one of the shafts, and is caused to revolve with it by a feather and slot; this engages with a similar jaw rigidly attached to the other shaft. This clutch enables shafts to be easily connected or disconnected while standing still, or even to be thrown out of gear while in motion; but it is obviously too sudden in its action to be used for connecting a shaft to one already running. For the latter purpose some form of friction or magnetic clutch is used.

Friction clutches are made in many different styles, the usual arrangements consisting of an inner ring which is expanded against

an outer ring; a rim which is grasped by jaws; or two cones that are forced together. The force is obtained by screws or toggle joints. Fig. 79 shows one type in which jaws carried by the shaft are caused to grasp a rim cast upon the pulley, the latter being mounted to turn freely upon the shaft when the clutch is released. The outer jaw on one side is carried by the same arm as the inner jaw on the other side; hence the grip is obtained by moving one arm upward and the other downward by means of the toggle operated by the collar on the left, which, in turn, is caused to slide on the shaft by a fork and lever controlled by hand. If used as a simple friction clutch to connect two shafts, no pulley is required, the rim being rigidly mounted upon one shaft and the jaws upon the other. The jaws are adjustable and are lined with renewable pieces of maple.

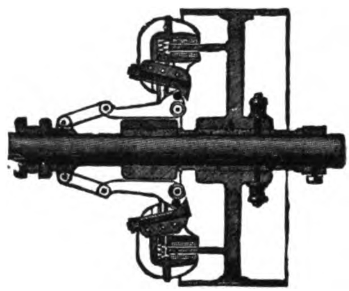


Fig. 79. Friction Clutch Pulley.

Magnetic Clutches.—The substitution of magnetic attraction for ordinary mechanical force, to obtain the friction required in a clutch, secures several decided advantages. The most important is the fact that the pressure is *self-contained*, the attraction being exerted only between the friction surfaces, without the end thrust or external force involved in all mechanical clutches. Complication of levers and pivots is avoided, the parts being few and simple. A magnetic clutch can be controlled from a distance and at several points. It is lighter and occupies less space for a given power transmitted. The form devised by Mr. B. J. Arnold, represented in Fig. 80, consists of two cast-steel rings A and B carried on steel webs E and F which are bolted to the hubs G and H fixed on the shafts J and K to be coupled. The magnetizing coil M is located in an annular slot in the field ring A, and is supplied with current through insulated rings on G. A brush-holder (not shown) is attached to the floor, wall, or ceiling. The armature B is separated $\frac{1}{16}$ to $\frac{3}{16}$ inch from the field A, according to size, when no magnetizing current flows. But the elasticity of the webs E and F allow the field and armature to spring together when the circuit is closed, the magnetic attraction holding the two in contact with great force. An Arnold clutch 48 inches in diameter will transmit 228 H.P. at 100

r.p.m. and consumes 2.58 amperes at 110 volts or 284 watts, being less than $\frac{1}{8}$ of 1 per cent. Several large electrical plants in Chicago,

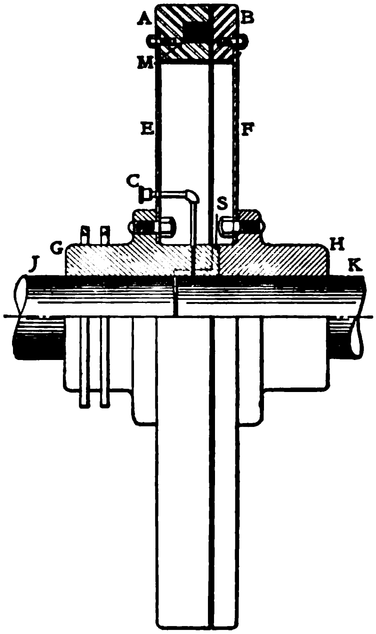


Fig. 80. Arnold Magnetic Clutch.

St. Louis, and other places employ these clutches to connect the various engines and generators.

CHAPTER XVI.

PRINCIPLES OF DYNAMO-ELECTRIC MACHINES.

Introduction.—The history of these machines has already been given in the general history of electric lighting in Chapter II.

A dynamo-electric generator is a machine for converting mechanical energy into electrical energy by causing conductors to move in a magnetic field, or *vice versa*. These machines operate according to the principle of magneto-electric induction discovered by Faraday in 1831.

Before taking up the consideration of the machines themselves, it is proper to give the principles of electro-magnetism, which play an important part in their construction and action.

Magnetic Field.—If an ordinary permanent magnet be approached by a small piece of iron or steel suspended on a thread, it will be attracted by the magnet. The space near the magnet in which this phenomenon takes place is called the *magnetic field*, or simply the "field." This region has no definite limits, since the distance at which magnetic effects can be obtained depends upon the sensitiveness of the instrument used. Delicate galvanometer needles, for example, may be deflected perceptibly at a distance of several hundred feet from the field-magnet of a large dynamo. It is customary, however, to consider the field as being confined to the immediate neighborhood of the magnet where the effect is strong. The extremities of a magnet usually exhibit magnetic properties more powerfully than the middle portions, and are called the *poles*. Magnetism is commonly regarded as consisting of a number of "lines of force" or "tubes of force." This conception was suggested by the lines in which iron filings arrange themselves under the influence of a magnet, the direction and intensity of the field being represented by the direction and number of the lines. This idea is often very convenient, but should not be taken too literally, as it sometimes leads to wrong notions.

The Magnetic Circuit.—To localize and strengthen the magnetic field, as well as to economize the wire and current required, the magnets of generators or other electro-magnetic apparatus are arranged in such a form that the path of the lines is as nearly as possible a closed circuit; that is, for the most part in iron, only a sufficient *air-gap* being left for the inductors and the clearance which they require for free motion. In Fig. 81 the general form of the magnetic circuit of a bipolar dynamo is shown, *CC* being the *magnetic cores*, upon which are wound or placed the *coils* or *bobbins* of copper wire *BB* through which the exciting current flows. *Y* is the *yoke* which connects the two cores, and forms with them the "horseshoe" type of magnet. The extremities of the magnet are provided with *pole-pieces PP*, which are bored out or shaped to receive the armature, which consists of the *armature core a* and *armature conductors* or "winding" *W*.

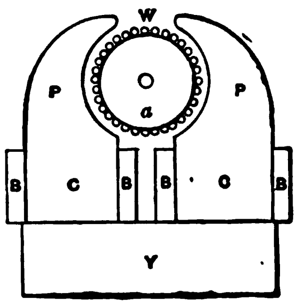


Fig. 81. Magnetic Circuit of Simple Dynamo.

Various other forms of magnet are used, but in almost every case they are equivalent to the horseshoe form shown; and even with *multipolar* field-magnets, that is, those having more than two poles, it is usually possible to consider them as being made up of several horse-shoe magnets, or, in other words, two or more magnetic circuits.

Calculations in regard to the magnetic circuit are usually made by means of a formula analogous to Ohm's law for the electric circuit, this expression being:

$$\text{Flux} = \frac{\text{Magnetomotive force}}{\text{Reluctance}}$$

There is, however, one important difference between this formula and Ohm's law; the reluctance is not a constant or an independent quantity like electrical resistance. It depends upon the value of the flux, or rather upon the flux density. Hence it is necessary to know the number of lines of force per square centimeter in the iron, in order to fix the value of the reluctance; whereas electrical resist-

ance has a constant value, and is independent of the strength of current, provided the temperature does not change. Furthermore, magnetic leakage is usually a much larger factor, and more difficult to determine, than electrical leakage, see data, pages 308 to 319.

Magnetic Flux.—The total quantity of "induction" or field in a magnetic circuit is called the *flux*, and is measured in *lines of force.* The term "line of force" was originally used by Faraday in a general sense to express the direction and intensity of magnetism in something the same way that the expression "ray of light" is used. When magnetism came to be measured definitely, the line of force was adopted as the unit of magnetic field or flux. If we follow the derivation of the value of the line of force, we find that a ***unit magnetic field*** exists at the distance of one centimeter from a ***unit magnetic pole***, the latter being a pole of such strength that it repels a pole of equal strength with a force of one dyne at a distance of one centimeter. Each square centimeter of the surface of an imaginary sphere with one centimeter radius described about a unit pole will contain a flux of one line of force; and since the total surface of the sphere is 4π, it follows that 4π, or 12.57 lines, emanate from a unit pole. This somewhat indirect definition is made much shorter and more convenient by simply stating that one hundred million lines of force cut per second generate one volt *E.M.F.* Since the values of the volt and other electrical units have been defined and legalized internationally, it is proper to base the magnetic units directly upon the electrical ones. Very frequently, instead of considering the total flux we treat the *flux density*, or intensity of magnetic field; that is, the number of lines of force per square centimeter. This quantity multiplied by the area of the field or cross-section of the magnet gives the total flux. The maximum flux density commonly used in practice is from 14,000 to 16,000 lines of force per square centimeter (90,300 to 103,200 per square inch) for wrought iron, and from 6,000 to 7,000, or about one-half as much, for cast iron. These values are what are called "practical saturation," beyond which it is not ordinarily economical to go. As a matter of fact, however, Ewing and other experimenters have forced magnetic density as high as 43,000 lines of force per square centimeter. On the other hand, in alternating-current transformers the ordinary flux density has a maximum value of only 4,000

to 6,000 lines, in order that the loss due to hysteresis shall not be excessive.

Magnetomotive Force, or Difference of Magnetic Potential.—This depends directly upon the *ampere-turns*; that is, upon the product of the number of turns of wire, and the number of amperes flowing through them—in fact, *M.M.F.* is often given in terms of the ampere-turns simply; but, strictly speaking, the *C.G.S.* value of *M.M.F.* is 1.257 times the ampere-turns. This is because the difference of magnetic potential on opposite sides of a turn of wire is equal to 4π times the current flowing in the wire; and since the ampere is one-tenth of the absolute unit of current, it follows that the ampere-turns must be multiplied by $\frac{4\pi}{10}$, or 1.257, to obtain the *C.G.S.* value of the magnetomotive force. The magnetic circuits of dynamos usually have from 3,000 to 10,000 ampere-turns, depending upon the length of the circuit, the air-gaps between the pole-pieces and the armature core, and the materials of, and magnetic density in, the field-magnet and armature.

Magnetic Reluctance.—The unit of this quantity is the reluctance between opposite faces of one cubic centimeter of space, i.e., vacuum; and as nearly all substances except iron and steel have practically the same magnetic reluctance as a vacuum, it follows that one cubic centimeter of almost any substance has practically one unit of reluctance. This is true of air, copper, brass, wood, paper, cotton, silk, mica, or other material, except iron or steel, that is likely to form part of the magnetic circuit. This fact, of course, tends to simplify magnetic calculations. The reluctivity of wrought iron varies from about .00033 at a flux density of 4,000 to .0031 at 16,000 lines of force per square centimeter. A few other metals besides iron, notably nickel and cobalt, have a reluctivity considerably less than unity; but they are so vastly inferior to iron as magnetic conductors that they are very rarely employed. It is also customary to consider the *permeability* of iron and other substances, this being the reciprocal of reluctivity.

Fig. 82 gives the magnetization curves for wrought and cast iron, cast steel and sheet steel, and shows the relation between *B*, the induction or flux density in lines of force per square centimeter, and the magnetizing force in ampere-turns (A.-T.), which multiplied by 1.257 gives the *M.M.F.* in *C.G.S.* units as already explained.

At a given density the flux per square inch is 6.45 times the flux per square centimeter, and the A.-T. necessary to produce this flux den-

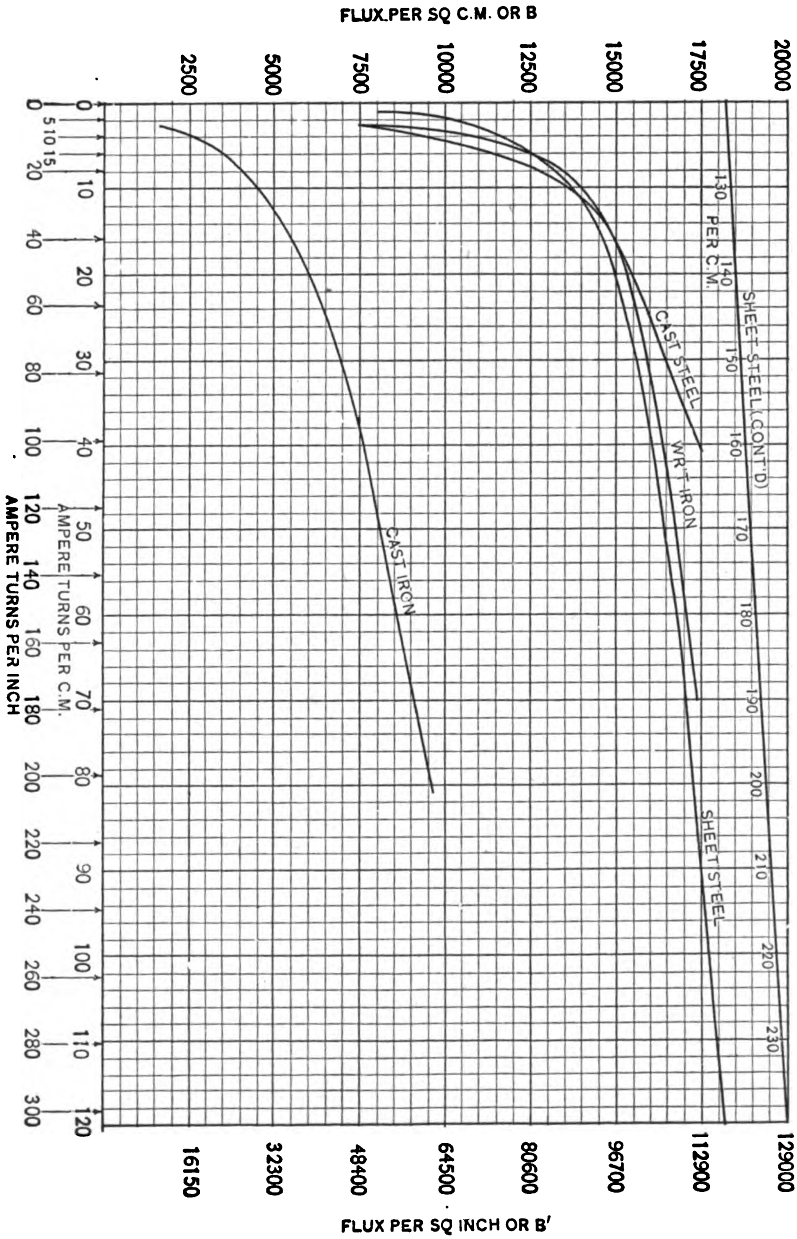


Fig. 82. Magnetization Curves.

sity per inch length of material is 2.54 times that required per centimeter. these values being also given on the curve sheet.

Calculations relating to magnetic circuits are later set forth under the head of field magnets. It is sufficient here to consider the simple case of a cast steel ring 20 centimeters internal and 30 centimeters external diameter, giving a mean diameter of 25 centimeters, or 78.5 centimeters in circumference. Assuming a flux density of 15,000 lines per square centimeter, reference to Fig. 82 shows that 16 A.-T. per centimeter length are required. Hence the magnetizing coil must have $78.5 \times 16 = 1256$ A.-T. It is not necessary to consider the cross-section of the ring, provided the flux density is known. In order to determine the total flux, however, we may assume that the ring is 10 centimeters thick, giving a cross-section of $10 \times 5 = 50$ square centimeters, and a total flux of $50 \times 15,000 = 750,000$ lines. The 1256 A.-T. required may be produced in any convenient way; for example, by 1256 turns carrying one ampere, 125.6 turns carrying 10 amperes, or other equivalent combination.

If the ring were cut and an air-gap of 2 centimeters introduced into the magnetic circuit, the additional *M.M.F.* required to produce the same flux density would be $2 \times 15,000 = 30,000$ *C.G.S.* units, which, divided by $1.257 = 23,866$ A.-T. This is nearly twenty times as great as that required by the steel portion of the circuit because of the very much lower permeability of air.

Magnetic Hysteresis.—When the direction or density of magnetic flux in a piece of iron is changed, a certain loss of energy occurs. This is due to the fact that the value of the flux lags behind, and does not correspond exactly with variations in the *M.M.F.* This phenomenon is shown in magnetization curves. In Fig. 82, for example, the value of B would be less in each case for a given value of H when the latter is increasing than when it is decreasing. According to Steinmetz,* the loss due to hysteresis is represented by the empirical formula: $W = \eta V f B^{1.6}$, in which W is the lost energy in watts, V the volume of the iron core in cubic centimeters, f the frequency of the magnetic changes in complete cycles per second, B is the maximum value of the flux density, and η is a coefficient depending upon the physical and chemical qualities of the material. For armature and transformer cores only the best

* "On the Law of Hysteresis," *Trans. Amer. Inst. Elec. Eng.*, vol. ix., pp. 3 and 621.

and softest sheet iron or mild steel should be used, the value of η for this material being between 2×10^{-10} and 3×10^{-10}. In most field-magnets the flux density is practically constant, hence hysteresis need not be considered. The usual hysteresis loss that occurs in good qualities of sheet iron employed in armature and transformer cores may be found from the curve in Fig. 83.

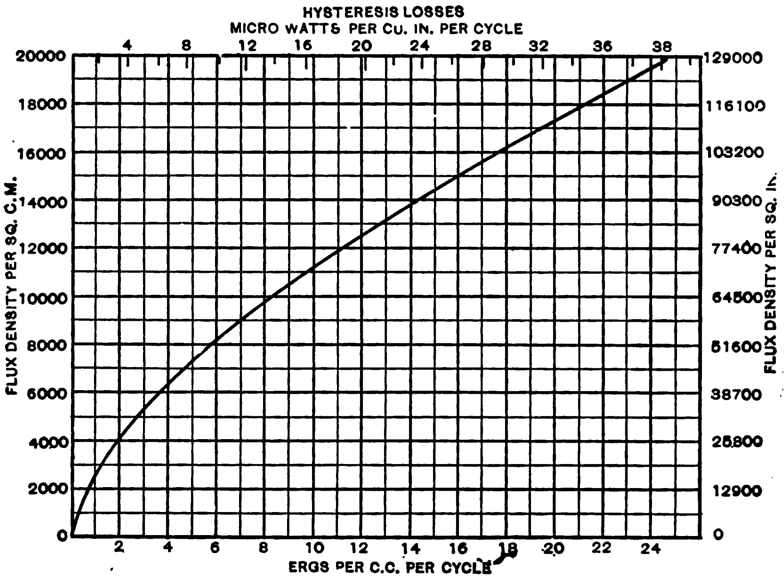


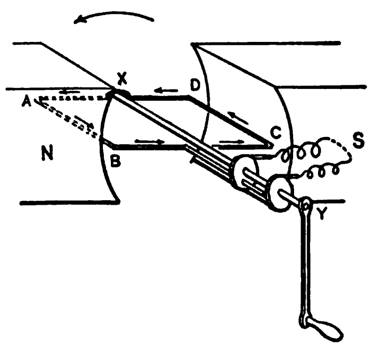
Fig. 83. Hysteresis Loss.

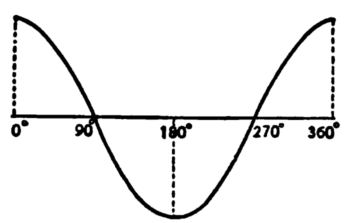
Generation of E.M.F.—Whenever magnetic lines of force are cut by a conductor, an *E.M.F.* is set up in it, the value of which is one volt when 100,000,000 lines are cut per second; or, in other words, it depends solely upon the *rate* of cutting, so that one volt is also set up if 1,000,000 lines are cut in one-hundredth of a second. In both cases the rate of cutting is supposed to be uniform throughout the given time.

The generation of *E.M.F.* is absolutely certain, no matter when or by what process the lines are cut. A *current*, however, is only produced when there is a closed circuit in which it may flow. A straight bar of copper, for example, cutting across a magnetic field, would have an *E.M.F.* set up in it, and an actual difference of potential would exist between its ends; but there could be no flow of current, except possibly a very slight displacement current at the moment when the *E.M.F.* is established. We should clearly

distinguish, therefore, between the generation of *E.M.F.* and of current. It may happen, also, that two or more opposing voltages neutralize each other, so that there is no current, even though the circuit is apparently closed. For example, when a copper ring is moved across a uniform field, the two halves cut an equal number of lines, and the *E.M.F.* in one half is exactly equal and opposed to that in the other half of the ring. In this case it is assumed that the ring is not rotated, or, in other words, is kept parallel to a fixed plane. Consequently, to generate an effective voltage and current in the ring, it is necessary to rotate it or have a magnetic field that varies in density, so that one side of the ring shall cut the lines in a different direction or cut more lines than the other. This explains the fact that the flux in a coil of wire must be varied to produce a current; or, in other words, the coil must be filled with, and emptied of, lines of force, in which case an alternating current is generated. This is often stated so broadly, however, that it seems to mean that an *E.M.F.* cannot be obtained in a uniform field. As already stated, an *E.M.F.* ***must*** be produced whenever magnetic lines are cut.

Elementary Dynamo.—The simplest form of dynamo consists of a loop of wire arranged to rotate in a uniform magnetic field, Fig. 84,

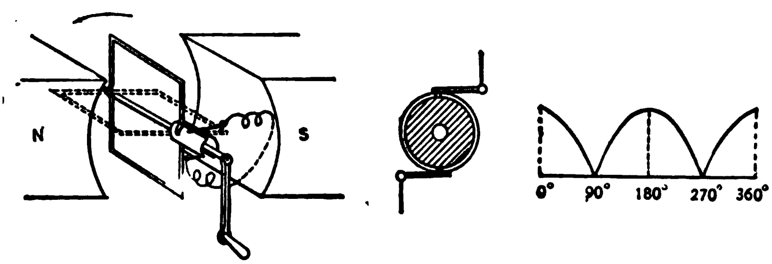




Figs. 84 and 85. Elementary Alternator and Curve of E.M.F. Generated.

and the generation of the electromotive force is as follows: Assume the loop with its plane parallel to the direction of the flux. If *then* the loop be rotated counter-clock-wise about its axis *XY*, the sides *AB* and *CD* which cut lines of force will have *E.M.F.'s* induced in them, that will tend to flow in the directions indicated by the arrows. The value of this voltage will depend upon the speed or

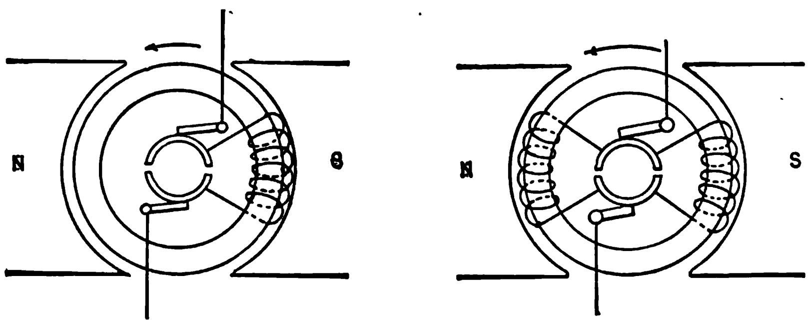
rate of cutting, and since this rate is greatest when the plane of the loop is parallel to the lines of force, the *E.M.F.* developed at the instant represented in Fig. 84 will be a maximum. As the loop approaches the 90° or vertical position, the voltage generated gradually reduces because the rate of cutting becomes less and at the 90° position reaches zero. If the rotation is continued the rate of cutting gradually increases until the 180° position is reached, where it becomes a maximum, hence the *E.M.F.* then generated is also a maximum. The cutting, however, is in the opposite direction to that occurring at first, so that the voltage is reversed, being negative with respect to that developed during the first 90° rotation. In passing from the 180° to the 270° position, the rate of cutting again decreases and the *E.M.F.* developed falls a second time to zero at 270°. While in the rotation from the 270° to the 360° position the rate of cutting increases and the direction of the *E.M.F.*



Figs. 86 and 87. Elementary D.C. Generator with Commutator and Curve of E.M.F.

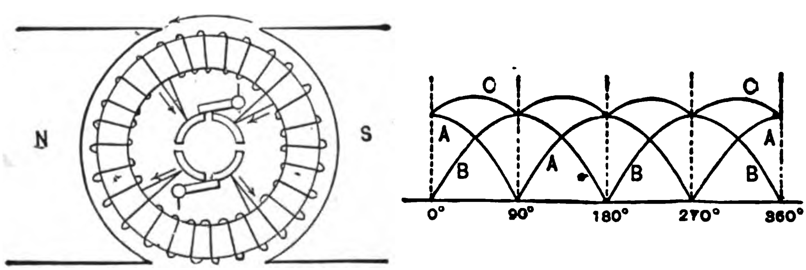
is the same as in the first 90° rotation, the *E.M.F.* rising once more to a maximum positive value at 360°, which is the same as the original 0° position. Plotting the various changes in value of the *E.M.F.* we obtain a curve as shown in Fig. 85. Such an *E.M.F.* is called an *alternating* one because of its reversal from positive to negative values, that is, it tends to produce a current first in one direction and then in the other direction through the circuit. If, however, it is desired to supply the external circuit with a *direct* or *continuous* current or *E.M.F.* a special device called a *commutator* must be employed. In its simplest form the commutator consists of a metallic tube, slit longitudinally into two equal parts, and mounted on a cylinder of insulating material, each half being connected to one terminal of the loop, as indicated in Fig. 86. Against this com-

mutator at *diametrically* opposite points press a pair of conducting pieces called *brushes*, which lead away the current to the external circuit. If these brushes are so set that each half of the split tube moves out of contact with one brush and into contact with the other brush, at the instant that the loop passes through the plane in which there is no cutting of the magnetic lines the alternating current induced in the loop will be rectified and caused to flow in one direction through the external circuit. If the external current be plotted it will be of pulsating character, as represented in Fig. 87. This explanation is not changed if, for the single loop, we substitute a



Figs. 88 and 89. Elementary Dynamos with Iron-Ring Armatures.

coil wound on an iron ring, as shown in Fig. 88. Now place an exactly similar coil diametrically opposite the first, and when its terminals are connected to the same two half-rings, as in Fig. 89, the two coils are in parallel, and though the voltage generated by



Figs. 90 and 91. Four-Coil Armature and Curves of E.M.F.

revolving this winding with two coils is no greater than with one coil, the current capacity of the resultant winding is evidently doubled. The current obtained from this winding through a two-part com-

mutator is very fluctuating and would be much steadier if two other coils were added and placed 90° from the first set, so that when one set of coils is at a zero position, the other set is generating a maximum *E.M.F.* To connect this winding properly with the external circuit, a four-part commutator is required, and the coils are connected, as shown in Fig. 90. The curve *C* in Fig. 91 represents the resultant *E.M.F.* at the brushes, and the curves *A* and *B* represent the *E.M.F.'s* generated respectively by each set of coils, the latter being one-quarter of a revolution, or 90° behind the former. It is noticed that not only is the *E.M.F.* steadier, but also greater, being never at any point below the maximum values obtained by a single set of coils.

On examination of the winding represented in Fig. 90 it is apparent that the four coils are wound in series, the end of the first

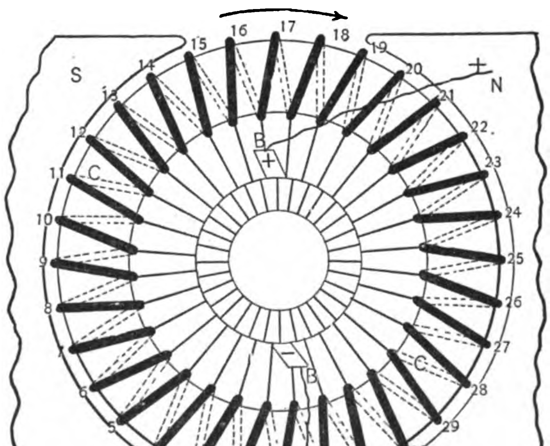


Fig. 92. Gramme-Ring Armature.

being connected to the beginning of the second, and so on, the end of the fourth being connected to the beginning of the first. This is known as a closed-coil winding, being closed upon itself, and will be discussed fully later because it is almost the only kind used in direct-current machines. As actually constructed, the coils or sections of winding and the corresponding commutator parts or sections are increased in number to obtain a practically steady

E.M.F. and to reduce the potential difference between adjacent commutator sections. This particular form of closed-coil armature is called a *Gramme ring*, invented in 1870, being represented diagrammatically in Fig. 92. This and other windings are treated in more detail under the head of armature windings.

CHAPTER XVII.

CONSTRUCTION OF DYNAMO-ELECTRIC MACHINES.

Parts of Dynamo-Electric Machines.—The essential parts are the *armature* and its winding, the *field-magnet* and its winding, and the *insulation* employed to separate the various parts of these windings. The field-magnet is usually stationary in direct-current machines, and is combined with the base and bearings to form the *frame* of the machine. It has already been shown that a *commutator* is necessary in the case of a direct-current machine, while alternating current generators are provided with *collecting-rings.*

In either case *brushes* are required to take off the current from the revolving commutator or collecting-rings. In most of the later types of alternator the armature is stationary, and the field-magnet revolves; hence the field-current must be supplied to the moving magnet by a similar pair of brushes and rings. The complete machine comprises also the shaft, oiling devices, and other mechanical details.

In considering the materials and proportions of the various parts of dynamos, the construction of the armature is taken up first, since it is the portion in which the current is generated, and usually its type and size are determined or approximated in the first place, the field-magnet, base, and other parts being made to conform to the armature.

Forms of Armature.—Any electrical conductor, as, for example, a simple coil of wire revolving or moving in a magnetic field, would act as an armature, and would tend to have an electromotive force set up in it as already explained. In order, however, to obtain the maximum effect with a given amount of material, and to secure compactness, convenience of working, and other practical conditions, the armature is usually made in one of two forms,—the *ring armature*, and the cylinder, or *drum armature.* In the former type the copper conductors are wound or placed upon an iron core

of ring form, the conductors being carried through the interior of the ring, as well as around the outside (Fig. 92). In the drum type the conductors are located wholly on the surface or ends of a cylindrical iron core (Fig. 93). In both cases the function of the iron core is twofold: first, it bridges across between the pole-pieces and conducts the lines of force, thus greatly reducing the reluctance of the magnetic circuit; and, second, it affords a solid support to carry the electrical conductors. Two other forms of armature are sometimes employed. One of these is the *pole armature*, in which conductors are wound around radial iron cores projecting outward from a central hub; and the other is the *disk armature*, in which the conductors are arranged in the form of a flat disk, the plane of which is perpendicular to the shaft. This last style of armature is rarely used, but it is the only one not requiring an iron core, since it rotates in a narrow space between the pole-pieces.

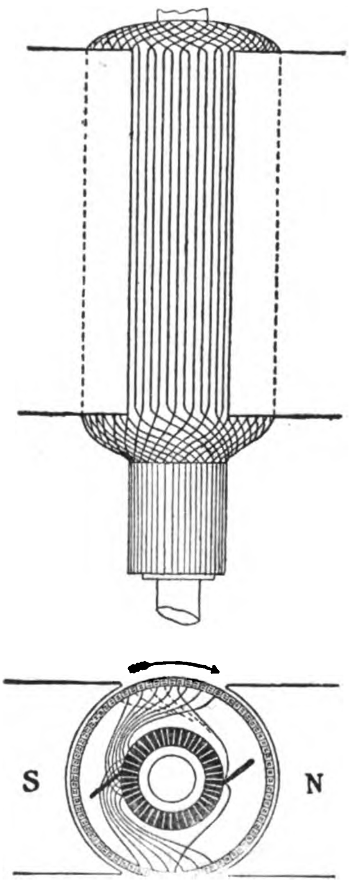


Fig. 93. Drum Armature.

Construction of Armature Cores.—Originally the core was made of one solid piece of iron; but this permits electric currents to be set up in it, because the outer portions of the core, like the armature conductors themselves, cut magnetic lines. The useless currents thus generated, called *Foucault* or *eddy currents*, flow in the same general direction as the useful armature currents. In order to minimize these eddy currents, which consume power and may cause excessive heating, their path is interrupted by subdividing, or *laminating* the core perpendicularly to the shaft. The usual plan is to build up the core of disks or rings of sheet iron or steel insulated

from one another, so that the magnetic lines can pass freely through each disk; while the eddy currents, tending to flow perpendicularly to them, are stopped by the insulation between. Hence the core should always be laminated parallel to the lines of force and to the direction of motion.

Disks or rings are used in nearly all cases for armature cores, and are punched out of the softest sheet iron or mild steel, from .015 to .025 inch thick. In armatures of small size each disk is a complete circle in one piece, but armatures of large diameter are built up of a number of segments. The laminæ are insulated from each other by tissue paper, paint, varnish, or simply by rust on the surface of the plates. Ordinarily, rust on both surfaces, and paper at every third or fifth plate, are sufficient. This usually brings the loss from eddy currents down to about one per cent. It is hardly economical to attempt further reduction, since the trouble of punching and handling many sheets of very thin iron, and the loss of space between the plates, more than offset the gain.

An armature core, built up as above described, with the plates forced together by heavy hydraulic or screw pressure, is found to consist of from 85 to 95 per cent iron, the remainder of its volume being made up of insulation, scale, etc.; hence the *effective* cross-section or magnetic flux-carrying capacity of such a core is from 5 to 15 per cent less than that of an equal volume of solid iron of the same dimensions.

Slotted and Perforated Armatures.—The core is often provided with slots or perforations in which the conductors are laid. This type, of which three forms are indicated in Fig. 94, also known as the toothed armature and sometimes called the Pacinotti armature, after its inventor, has the following advantages over the smooth core:—

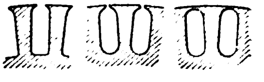


Fig. 94. Slotted and Perforated Armature Cores.

1. The reluctance of the air-gap is reduced to a minimum.
2. The armature conductors are protected from mechanical injury.
3. The conductors are firmly held in place, and cannot slip on the core by the action of the electrodynamic force exerted upon them, which in a smooth core is equal to the total torque.
4. Eddy currents in the armature conductors are avoided, since the lines snap across the latter instantly.*

* See a paper on "Magnetism in Its Relation to Induced *E.M.F.* and Current," by Elihu Thomson, *Trans. Amer. Inst. Elec. Eng.*, vol. vi., p. 269, 1889.

5. If the teeth are practically saturated by the field-magnetism, they oppose the shifting of the lines by armature reaction (which will be considered later).

The disadvantages of a slotted armature core are:—

1. It is somewhat more expensive to make on account of the trouble of punching and insulating the slots.
2. The teeth tend to generate eddy currents in the polar faces.
3. The self-induction of the armature coils is increased.
4. Increased hysteresis loss, due to denser flux in the teeth.
5. Leakage of lines of force through the armature core, extericr to the wind ng, particularly in the case of partly inclosed slots or perforated cores.

The second objection can be practically overcome by making the air-gap at least 50 per cent of the distance between the teeth, so that the lines of force can spread from the corners of the teeth, and become nearly uniformly distributed over the polar faces. With air-gaps less than this, the pole-pieces should be laminated in the direction of the motion of the armature. The leakage mentioned in the fifth objection can be made negligible if the amount of metal above the conductors be kept very small.

The ratio of tooth width to slot width, for most efficient operation, has been found to exist when the width of the tooth is about equal to the width of the slot minus twice the thickness of the slot insulation, or, in other words, the metallic area of the teeth should equal that of the copper conductors in the adjoining slot.

Hysteresis in Armature Cores.—The general nature and amount of the hysteresis loss has already been given in connection with Fig. 83. It is greatly affected by the quality of the iron. That employed by the General Electric Company has the following composition:—

Iron................	99.89	to	99.76	per	cent
Sulphur.............	.04	"	.08	"	"
Silicon..............	.005			"	"
Phosphorus	.04	"	.08	"	"
Carbon.............	.06	"	.10	"	"

The armature disks are punched from large sheets about .025 inch thick. Since the edges are considerably hardened by the punching, it is well subsequently to anneal the iron by raising it to a bright red heat and allowing it to cool very slowly. This

heating also has the effect of burning off the burr from the edges of the disks, and oxidizes their surfaces so that they are partially insulated from each other with respect to eddy currents.

Size and Form of the Armature Core.—There is no absolute rule for determining the size of an armature, since it depends upon many conditions which cannot be included in a formula or covered in any general way; nevertheless there are several facts that will aid one in assuming an approximate size, that can be modified later if found incorrect. The chief points to be considered in arriving at the size of an armature core are:—1. Peripheral speed. 2. Space for inductors. 3. Surface covered by pole-pieces. 4. Flux-carrying capacity. 5. Cooling surface.

Peripheral Speed.—One guide for determining armature diameter is the fact that the peripheral velocity should be kept between 1,500 and 6,000 feet per minute, 3,000 being a common value. The peripheral speed of an armature is the product of its circumference in feet by the number of revolutions per minute, or

$$V = \frac{D_a''\pi}{12} \times \text{r.p.m.},$$

from which the approximate diameter D_a'' in inches can be found.

Flux Density in Armature Cores.—The length of the armature core must next be considered, and this depends primarily upon the width of the polar face and the amount of the spreading or "fringing" of the lines of force. The latter may be determined by adding .8 of the length of the air-gap to the polar width. The diameter of the core having already been determined by peripheral speed limitations and the width of the core by the conditions of fringing, its proper radial depth can be readily found from the cross-section to be provided for the passage of the lines of force. The number of lines permitted per unit area of cross-section is limited by the heating of the armature due to hysteresis and eddy current losses, the heat generated by either of these phenomena being greater the denser the flux or the more rapid the magnetic reversals. Hence, allowable flux densities are less with high-speed than with lower-speed machines, and likewise less with multipolar than with bipolar forms.

The following table gives the armature core densities usually employed in practice for various kinds of armatures:—

Class of Machine.	Form of Armature.	Speed.	Flux Density per Square Inch.
Constant potential bipolar D.C. generator or motor	Drum	High	50000–70000
		Low	60000–90000
	Ring	High	60000–80000
		Low	80000–100000
Multipolar D.C generator or motor	....	High	35000–60000
		Low	50000–80000
Constant potential A.C. machines	....	....	35000–45000
Constant current D.C. arc machines	....	....	100000–130000

The cross-section of each armature inductor may be estimated by the current it must carry, from 600 to 800 circular mils per ampere being usually allowed. The number of paths through the armature between which the total current is divided must also be known. In bipolar, closed-coil windings there are two paths, and each inductor must carry one-half of the total armature current. A four-pole closed-coil winding may be either two or four circuit, as will be explained under methods of armature winding; hence, the exact method of winding must be decided upon. The number of armature inductors is determined by the *E.M.F.* to be generated and is given by the following formula:—

$$S=\frac{60\times 10^8\times E}{n\times N},$$

in which S is the total number of inductors counting all around the armature, n is the number of revolutions per minute, and N is the flux in lines of force entering the armature from one pole-piece. This applies to all armatures in which the paths for the current equal the number of poles, but must be modified for the two-circuit multipolar windings, or the double windings described later. The only general rule is the simple fact that 10^8 lines of force cut per second induce one volt, and the *E.M.F.* generated by one inductor must be multiplied by the number of them in series between the + and − brushes.

Having approximated the number and size of the inductors and the dimensions of the armature core, it may be necessary to readjust either or both of them so as to satisfy limitations due to heating or radiating surfaces, considered later.

Even for a given *E.M.F.* it is possible to design a short core

of large diameter, or a long core of small diameter; and nothing but experience and circumstances indicate which is the better. From the nature of the case there is no direct or royal road to the design of an armature, it being usually necessary and always desirable to draw several different modifications, in order to compare them and select the best.

Mounting of Armature Cores.—The cores of small drum armatures may consist of disks of sheet iron having a central hole only large enough to slip on the armature shaft (Fig. 95). They are

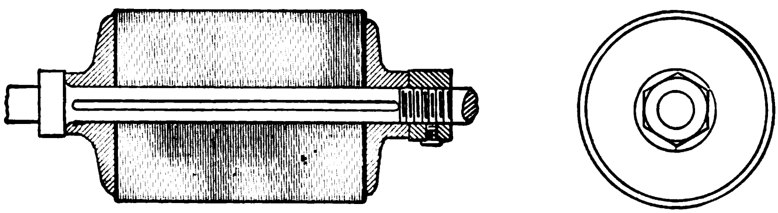


Fig. 95. Mounting of Small Armature Core.

held together either by large nuts screwed directly on the shaft, or by bolts passing through the core from end to end, holes being punched in the disks for the purpose. These bolts must be insulated from the core by tubes and washers of paper, fiber, or mica, otherwise strong currents will circulate through them, involving a serious loss of energy. The disks being very thin, a thicker plate of cast or wrought iron or other metal should be put at each end. The rims of these plates should be beveled quite thin, so that eddy currents shall not be set up in them.

The armature core has the full torque exerted upon it by the conductors, consequently it must be firmly connected to the shaft in order to be driven positively. Furthermore, in toothed armatures it is particularly important to preserve the alignment of the disks. The usual plan is to cut slots in the disks and shafts, in which a key is placed, as represented in Fig. 95.

In ring armatures, and in drum armatures of considerable diameter, the interior of the core is removed, making it necessary to support the core on some form of spider. This consists of a hub mounted upon and keyed to the shaft, with radial arms which are bolted or otherwise connected to the armature core. A simple and strong construction comprises two spiders, between the projecting

arms of which the core is held by bolts passing completely through both spiders and the core. This requires, however, a certain portion of the core to be cut away by the bolt-holes, and necessitates insulating the bolts from the core and the spiders. These objections are obviated by clamping the disks between flanged spiders forced together by bolts inside of the core (Fig. 96), or by nuts on the shafts in the case of smaller armatures.

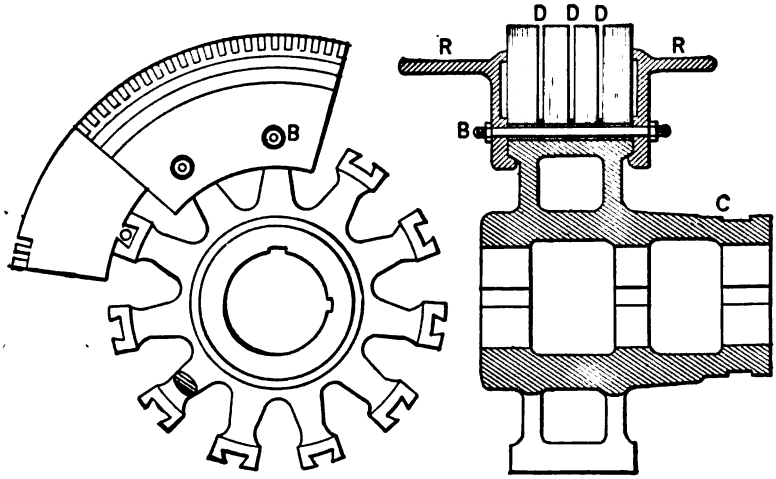


Fig. 96. Mounting of Large Armature Core.

Armature shafts are made of machinery steel, and are usually much thicker in the middle than at the ends (Fig. 97), as they must

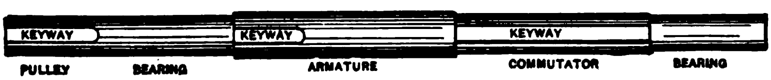


Fig. 97. Armature Shaft.

be exceedingly stiff to withstand the powerful magnetic side-pull on the core, if the latter is even slightly nearer one pole-piece than the other, especially in multipolar machines. The shoulders obtained by having the shaft larger in the middle serve to keep the armature in the proper position with respect to the bearings, and also enable nuts to be screwed on the shaft to hold the armature core, spiders, commutator, etc., in machines of small or moderate size. The torsional strain in armature shafts is often considered, but compared with the transverse strength required it is usually insignificant.

Finishing the Amature Core.—The core should have all sharp or rough edges removed, by filing or otherwise, before the conductors are put on. The disks should be punched so true in the first place that it is not necessary to turn the core in a lathe.

Armature Insulaticn.—The core must now be thoroughly insulated. This might be partly accomplished by covering the completed core with one or more coats of Japan or enamel; but this insulation cannot be relied upon to any great extent, as it is very likely to have minute holes or bubbles in it, or be pierced by particles of metal or by the rough edges of the disks. Therefore, two or more layers of strong paper, fiber, canvas, or mica, or a combination of these, should always be applied to the core where the conductors are to be laid. A smooth core is entirely covered in this way, but with a toothed core the insulation is usually put in the form of separate troughs in the slots between the teeth. The ends of the core should be insulated with thicker material, since the strain upon it is greater, particularly at the edges.

ARMATURE WINDINGS.

Armature conductors, or **inductors,** as they are called, since the *E.M.F.* is generated in them by magneto-electric induction, are almost universally made of copper. The ordinary form consists of simple copper wire, insulated with a double or triple covering of cotton; but rectangular bars or cables of twisted wires are also used. It is not convenient to handle wire larger than about No. 8 B. & S. (.1285 inch diameter); consequently two or more wires are wound together, or connected in parallel, if a larger conductor is needed. Copper bars or cable may be used when the amount of current is sufficient to require them. Bar inductors are liable to have eddy currents set up in them, because the edge entering or leaving the field generates a higher *E.M.F.* than the other, as represented in Fig. 98. The resulting loss may be serious with large bars. It is reduced by making the bars thin tangentially; by causing the edge of the bar to enter the field gradually, either varying the air-gap or shaping the pole-pieces so that the edge of the field is not parallel

Fig. 98. Eddy Currents in Bar Inductors.

to the inductors; and by using cables of twisted wires. It is not necessary in the last case to insulate the strands from each other very perfectly, a film of oxidation or varnish being sufficient, since the differences in *E.M.F.* are small. The various means for overcoming this difficulty are given by Hawkins and Wallis.* With the slotted armatures now generally employed, trouble from this cause is much less than with smooth cores, because the magnetic conditions are practically uniform throughout each slot at a given instant, except with large slots or with rapid reversals of magnetism, as in alternating-current generators.

Methods of Armature Winding.—The arrangement of the inductors, and the order in which they are connected together to form a complete "winding," constitute one of the most complicated subjects in electrical engineering. This matter is elaborately treated by Parshall and Hobart in a large work entirely devoted to it,† and most of the books on dynamos and motors give considerable space to this subject, notably those by S. P. Thompson,‡ and Hawkins and Wallis.§ A small work by E. Arnold ‖ contains nearly all of the important methods for direct-current machines.

Formerly the wires were always wound upon the core, each turn being put in place by hand. That method is still used for perforated armatures (Fig. 94) and in small machines. Such a winding, however, has rarely if ever been made with one continuous wire. For convenience of handling, also to facilitate connection to the commutator, it is customary to use comparatively short pieces of wire sufficient only for one section of the winding. In direct-current armatures the number of these sections or coils is usually equal to the number of commutator-bars. In alternating-current armatures their number equals the number of field-poles for single-phase and is correspondingly increased for two- or three-phase working. About 1890 the practice was introduced of winding these coils separately on forms and then placing them on the armature core as another operation. This plan, employing the so-called

* *The Dynamo*, London, 1903, pp. 341–344.

† *Armature Winding for Electric Machines*, New York, 1895.

‡ *Dynamo Electric Machinery*, London and New York. Also *Design of Dynamos*, London and New York, 1903.

§ *The Dynamo*, London, 1903.

‖ *Armature Winding*, translated by F. B. de Gress, New York.

"formed coils" illustrated in Fig. 99, saves much time and labor; in fact, the total time or expense required to make the coils and apply them to the armature is often less than one-quarter of what it was for the old-fashioned method of winding.

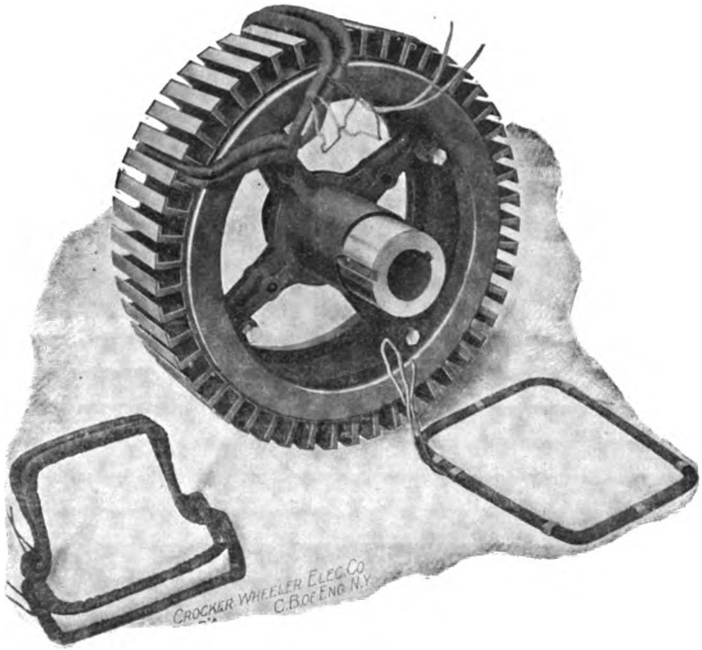


Fig. 99. Partly Wound Drum Armature with Formed Coils.

With either style of winding the coils are all connected together in most cases, the end of one being joined to the beginning of another, and so on. For alternating-current armatures the coils are usually arranged in this way as one simple series for each phase, the terminals being connected to the external circuit either directly or through slip-rings. The coils of direct-current armatures are almost always connected in a similar manner to form one series, but this is closed on itself; that is, the end of the last coil is joined to the beginning of the first one. This produces the *closed-coil* winding already represented (Fig. 92) that is universally adopted in direct-current generators and motors, except in the Brush and the Thomson-Houston series arc-lighting dynamos (Chap. XVIII), which have *open-coil* armatures, but are special machines used only for the purpose named.

One other important exception to the simple closed-coil winding for direct currents is the double or multiple winding described later and consisting of two or more separate windings, each complete in itself.

Direct- and Alternating-Current Windings.—In classifying armature windings, the most prominent distinction is between those intended for direct, and those for alternating currents. All armature windings have alternating currents generated in the inductors themselves, which are led out without change when that character of current is desired, but which must be *rectified* and made to flow in one direction only by means of a commutator in order to obtain a direct current. Consequently, a commutator is the distinguishing accompaniment of a direct-current winding. There is no necessary difference between the windings for the two purposes, since a direct-current armature can be made to give an alternating current by connecting two complementary points of the winding to a pair of collecting-rings as in a rotary converter or a double-current generator described later. In practice, however, direct-current windings are usually quite different from those designed for alternating currents, as shown by comparing the diagrams that follow.

Bipolar and Multipolar Windings.—The form of the magnetic field in which the armature is to revolve largely influences the method of winding the latter. Formerly nearly all direct-current dynamos and motors were bipolar, but now the tendency is to build machines of more than two or three kilowatts capacity with multipolar fields. For moderate sizes, four or six poles are customary, but for large machines eight to twelve poles are employed. Practically all alternators are multipolar, in most cases the number of poles being large, and equal to twice the frequency divided by the number of revolutions per second.

Ring Winding.—The chief structural difference between armatures depends upon whether the inductors lie entirely upon the external surface, or are carried through the interior of the core, the former being called a drum winding and the latter a ring winding (Figs. 92 and 93). The actual form of the core does not determine the question, since large drum windings usually have ring-shaped cores, the interior of the core being superfluous.

In Fig. 92, which represents diagrammatically a ring armature, *CC* is an armature core of laminated iron carrying inductors 1, 2, etc.,

and revolving clockwise in a bipolar field formed by the two poles *N* and *S*, the magnet itself not being shown.

The winding extends completely around the core, and is closed at the starting-point as represented. The entire winding could be made of one piece of wire, but it is more convenient to make it in sections connected together, as already explained. The conductors on the inside of the ring cut no lines, except those due to a slight magnetic leakage; hence practically no *E.M.F.* is generated in them. Their only function is to complete the circuit, and carry the current back to the successive inductors. It is also a fact that little or no *E.M.F.* is produced in the neutral spaces between the pole-pieces. The inductor 1, for example, is idle at the moment represented, and 3 is just entering the field and beginning to generate. It is, therefore, evident that starting with inductor 1, the potential gradually rises, each inductor adding a certain amount, until No. 17 is reached, beyond which the potential falls, since the *E.M.F.* is set up in the opposite direction under pole *S*, and finally it decreases to the original value at the starting point.

If two stationary brushes were placed at the points 1 and 17 respectively, so as to touch the winding as it revolves, the upper one would be positive and the lower one negative.

The brushes have been applied directly to the winding in some types of dynamo; but usually the winding is tapped off at a number of points, and connected respectively to the segments of a commutator, on which the brushes *BB* rest.

Multipolar ring armatures may be made exactly the same as the bipolar form just described. All that is necessary is to run it in a multipolar field. A Gramme ring in a four-pole field is represented in Fig. 100. With any direct-current multipolar machine there is one positive point and one negative point on the commutator for each pair of poles, the brushes being applied at these points, as in Fig. 100. A four-pole dynamo may be regarded as a combination of two bipolar machines, one with six poles as consisting of three bi-polar machines, and so on. A circuit from one + and one − brush could be brought out independently, and another circuit from the other two brushes, but usually the two + and the two − are respectively connected together, the total current being combined in two conductors, as shown.

Multiplication of E.M.F. in ring armatures may be accom-

plished by simply increasing the number of turns. For example, in Figs. 92 and 100, each section included between two commutator connections consists of one turn of wire. The substitution of two turns for the single turn in each section would double the *E.M.F.* generated, and so on for any number of turns per section. Hence, the *E.M.F.* may be multiplied in this way to any practical value, ring armatures for series arc lighting (Chap. XVIII) having been successfully used to give 5,000 to 10,000 volts, but ordinarily direct-current generators as well as motors are not operated at more than

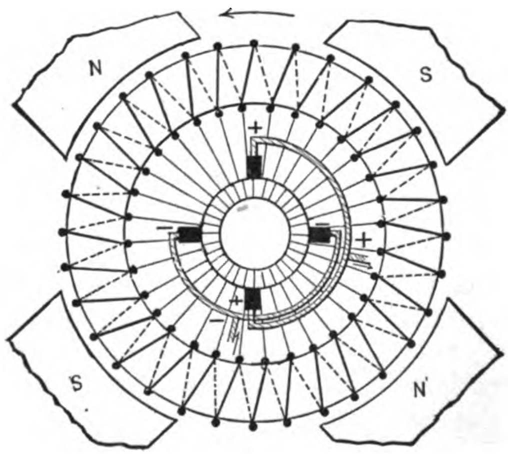


Fig. 100. Ring Armature in Four-Pole Field.

600 volts. The *E.M.F.* being directly proportional to the number of turns of wire, other things being equal, it is not necessarily changed by altering the number of sections or commutator-bars. For example, a winding consisting of 32 sections of 2 turns per section would generate the same *E.M.F.* as one having 64 sections of a single turn each or 16 sections of 4 turns per section. The number of sections is usually equal to the number of commutator-bars, which must be sufficient to subdivide the total voltage, so that the potential difference between adjacent bars is not high enough to produce injurious sparking. This is preferably limited to less than 20 volts, but depends upon various conditions that will be considered later.

Drum Windings.—As explained in relation to Fig. 92, the drum differs from the ring winding in the fact that the conductors lie wholly upon the external surface of the core, and do not pass through

the interior of the latter even when it is of ring form, which is usually the case. The principle of the drum winding is indicated in Fig. 101.

It will be noted that a conductor (No. 1, for example) is brought forward under one pole, N, and back (at No. 6) under the other pole, S, and so on until the winding is completed. This is a necessary condition in a drum winding, since a neutralizing *E.M.F.* would be generated if the wire passed back under the same pole. In the ring this neutralization is avoided by carrying the conductor

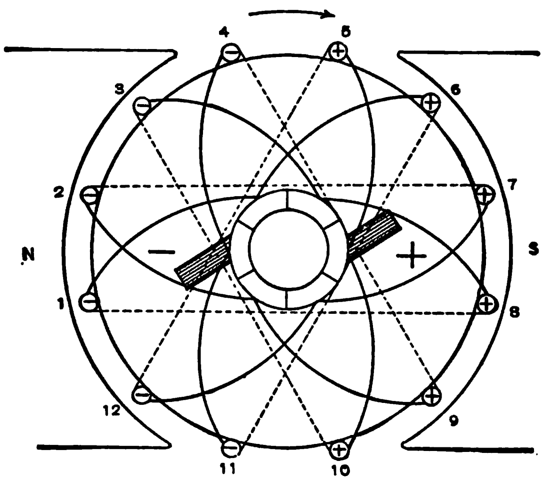


Fig. 101. Original Bipolar Drum Winding.

back through the inside of the ring where practically no *E.M.F.* is set up. Hence each inductor of a drum armature must be connected to one at a sufficient distance to be acted upon by opposite magnetic polarity. In other words, there are two active parts in each turn of wire one under pole N and the other under pole S. Whereas there is only one active portion in each turn of a ring winding; and furthermore, the latter is almost invariably connected to another turn lying close to it.

A further distinguishing characteristic is the fact that the conductors of a drum armature cross each other, as shown in Fig. 101, while the turns of a ring winding lie nearly parallel (Fig. 92). Finally, neighboring wires may have great difference of potential in the former, but differ only slightly in the latter. All of these points are in favor of the ring type, nevertheless it is employed very much less than the drum, and its use is steadily decreasing. This is partly

due to the larger percentage of inactive wire, but is chiefly the result of adopting formed windings (Fig. 99), which can be readily applied to drum but not to ring windings. Self-induction is also less in the former, so that commutation difficulties are reduced, as explained later.

The winding represented in Fig. 101 is that devised by von Hefner-Alteneck, who originated the drum armature in 1873. There is almost no limit to the number of possible windings, and very many different forms are actually used, but they may be grouped in certain classes. In Fig. 101 inductors marked + carry current toward the observer, and those marked − carry it away from him.

It is evident that each single conductor in any drum winding may be replaced by two or more, just as each section of a ring armature may consist of one turn or any number, as already explained.

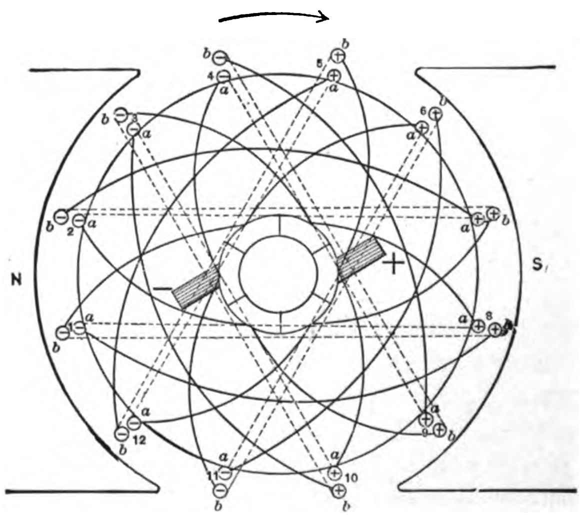


Fig. 102. Bipolar Drum Winding with Two Turns per Section.

For example, Fig. 102 represents a drum winding which is the same as the simple form in Fig. 101, except that the number of inductors is doubled, the arrangement of the wires and the number of commutator-bars remaining the same. If revolved at equal speed in the same magnetic field the *E.M.F.* would also be doubled, but the allowable current would be only one-half as great, because it would be practically necessary to use a wire of one-half the cross-section in order to put twice as many turns in the same space. This

result of doubling the *E.M.F.* can also be obtained from the drum winding in Fig. 103, which has twice as many sections as that in Fig. 101, each consisting of a single turn. In that case the number of commutator-bars would also be doubled, as shown.

Cross-connected Multipolar Armatures.—The four-pole ring armature shown in Fig. 100 requires four brushes to obtain the full current from the armature. If diametrically opposite points all

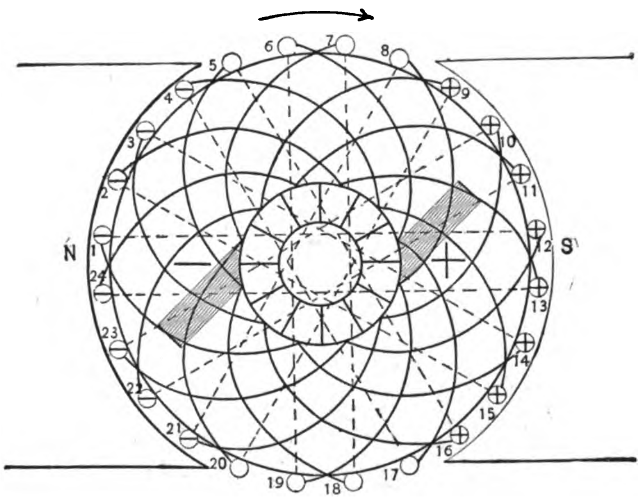


Fig. 103. Bipolar Drum Winding.

the way around the winding are permanently connected together, the upper + brush, for example, will also receive the current from the opposite point by the cross-connection, the same being true of either – brush; hence, two brushes will take the whole current generated by the armature. The cross-connection may be made either in the armature itself or in the commutator. In a six-pole dynamo, three points 120° apart are cross-connected, four points 90° apart in an eight-pole machine, and so on.

An example of drum armature is illustrated in Fig. 104 in a partly completed condition. This type is adapted to direct connection with an engine of about 150 H.P., the shaft of which is extended to receive it. Modern drum windings are usually arranged entirely on the curved surface of the cylinder, being called *barrel windings*, whereas formerly the end-connections were located on the flat ends of the cylinder.

Two-Circuit Multipolar Windings.—In either the four-brush or the cross-connected windings just referred to, the current has four paths or circuits through the armature; and the current which flows out is the sum of four currents generated in the four quadrants of the armature. The same would be true if the two positive as well as the two negative brushes were connected together in parallel, which is usually done by means of metallic rings or flexible cables (Fig. 100) if the machine is not cross-connected internally. In a bipolar winding there are two paths for the current, this being the minimum number for any closed-coil winding. It is also possible to produce a multipolar winding which has only two paths. In

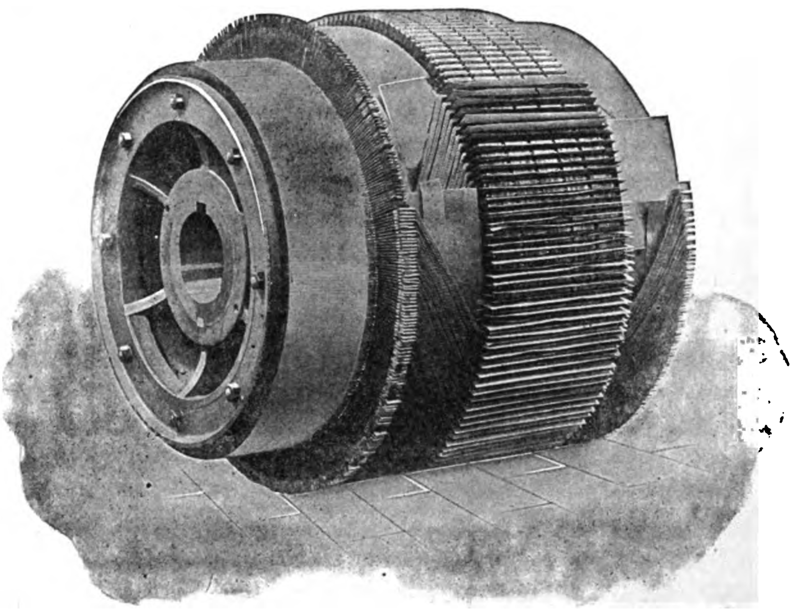


Fig. 104. Partly Wound Drum Armature of Medium Size.

Fig. 105, a drum winding is made with 22 inductors, the connection being made each time to the fifth inductor ahead, and the result is that two brushes applied to the commutator at *e* and *b* will take off the entire current generated, and there will be but two paths through the armature. If desired, brushes may also be placed at the two other neutral points in order to increase the area of contact. In such a winding the voltage is twice as great as that generated by a

winding with four paths, assuming the number of inductors to be the same.

This method of winding, called *series* or *two-circuit*, is produced on any multipolar drum armature when $C=ny\pm 2$, in which C is the number of inductors, n the number of poles, and y is the *pitch* or *spacing*. This last quantity is the number of inductors by which the winding advances at each end-connection, and must be *odd*, being 5 in the winding represented in Fig. 105. It is approximately

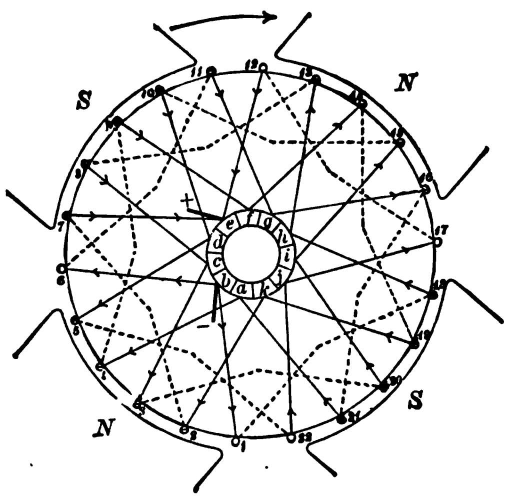


Fig. 105. Two-Circuit Multipolar Drum Winding.

WINDING TABLE.

1	front to	6	back to	11
11	" "	16	" "	21
21	" "	4	" "	9
9	" "	14	" "	19
19	" "	2	" "	7
7	" "	12	" "	17
17	" "	22	" "	5
5	" "	10	" "	15
15	" "	20	" "	3
3	" "	8	" "	13
13	" "	18	" "	1

equal to $\frac{C}{n}$, that is, the distance between the centers of adjacent pole-pieces, in order that the *E.M.F.* generated may be forward under one, back under the next, and so on, thus adding the effects in series. The pitch is not, however, exactly equal to that distance, being made a little less or a little greater, so that the position of the inductors gradually changes as the winding proceeds, otherwise they would pile up at certain points. In the winding shown in Figs. 105 and 106 $C=(4\times 5)+2=22$.

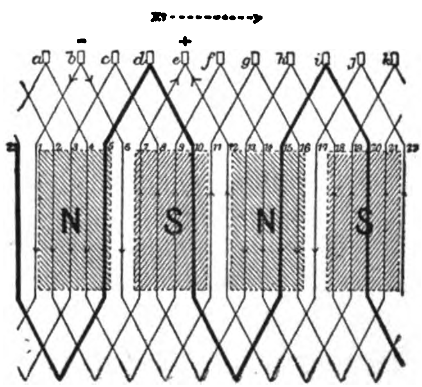
It is also allowable to employ a pitch at one end of the armature different from that at the other end, but *both must be odd and the difference must be 2*, hence the average pitch y_{av} is even. In this case the formula becomes $C=ny_{av}\pm 2$, giving another series of available windings, because y is odd in the first expression and y_{av} is even

in the second. This gives greater freedom for choice of windings, particularly for machines with six, eight, and higher numbers of poles. The use of the + sign in either of the above formulas makes y or $y_{av}=\frac{C-2}{n}$, that is, the spacing is *less* than the distance between centers of consecutive poles, and the end-connections are relatively shorter, which is advantageous, other things being equal.

Two-circuit multipolar ring windings may also be obtained, but are not used often.

Two-circuit windings in general secure the advantage that the number of inductors required for a given *E.M.F.* is one-half as great as in a four-circuit winding. This is because one-half of the inductors act in series in the former, while only one-quarter act in series in the latter. On the other hand, the cross-section of the inductors must be doubled for the same total current generated, because two paths in the former must carry as much current as four paths in the latter. These statements apply to four-pole windings, corresponding differences existing in other multipolar armatures.

Multiple-circuit drum windings, that is, those having as many paths as there are poles, are obtained from *any even number of inductors, but the pitches y at the two ends of the armature must both be odd and must differ by* 2, hence the average pitch is even. The

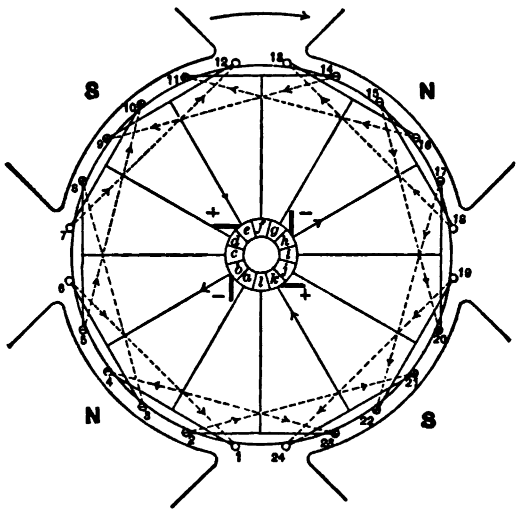


$$y_{\text{front}} = \text{odd number}$$
$$y_{\text{back}} = y_{\text{front}} \pm 2$$
$$y_{av} = \text{even number} = \frac{2y_{\text{front}} \pm 2}{2}$$

Fig. 106. Wave Winding. The same as in Fig. 105.

pitch is also forward at one end and backward at the other end, as in Fig. 107, which shows a winding of this kind. This gives what is called a lap winding, and will be compared with the wave

winding in Fig. 105. One pitch is usually a little greater and the other a little less than the distance between centers of consecutive



WINDING TABLE.

1	front	to	4	back	to	23
23	"	"	2	"	"	21
21	"	"	24	"	"	19
19	"	"	22	"	"	17
17	"	"	20	"	"	15
15	"	"	18	"	"	13
13	"	"	16	"	"	11
11	"	"	14	"	"	9
9	"	"	12	"	"	7
7	"	"	10	"	"	5
5	"	"	8	"	"	3
3	"	"	6	"	"	1

Fig. 107. Multiple-Circuit Drum Winding.

holes, so that the average pitch is nearly or exactly equal to that distance, i.e., in the latter case $y_{av}=\frac{C}{n}$. As explained in regard to two-circuit drums, it is generally desirable to make y_{av} less rather than greater, in order to shorten the end-connections, and for that reason windings have been made with both pitches less than $C \div n$. Usually the inductors in these windings are an exact multiple of the number of poles, that is, $C=nx$, in which x may be any number, odd or even, but greater than 3. The winding in Figs. 107 and 108 is obtained by making $C=4\times6=24$.

Windings with four or more circuits are exposed to the danger that if the *E.M.F.'s* generated by the several poles are not equal, currents tend to play back and forth between the sections. To take an extreme case, assume that the magnetizing coil is broken or short-circuited on one of the field-cores, so that very little *E.M.F.* is generated under the corresponding pole-piece. That portion of the winding then acts as a short circuit on the rest, and the armature may thus be burned out. There is, however, a fortunate self-regulating effect that tends to reduce inequalities of voltage in the different portions of such a winding. Assuming that a greater flux

exists between one particular pole-piece and the armature than in the case of any of the other poles, it will generate a higher *E.M.F.* in that portion of the winding then passing under it. This causes a relatively greater current to flow under that pole, which, reacting upon the flux, tends to reduce it to normal value. Conversely a weaker pole is less opposed by the smaller current or is favored by a reversed current, also tending toward equality of conditions. It is not wise to rely entirely upon this self-balancing, however, it being an easy

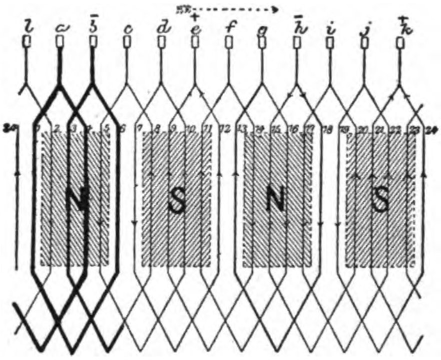


Fig. 108. Lap Winding. The same as in Fig. 107.

matter to test the voltages between adjacent sets of brushes all the way around the commutator to determine whether they are equal. If not, the voltages and fluxes corresponding to the different poles should be equalized by varying the number of turns in the field-coils, the simplest way being to take off or short-circuit some of them. This difficulty being easily avoided, does not seriously interfere with the use of multiple-circuit armature windings; in fact, they are generally employed in direct-current machines.

An advantage of the two-circuit armature winding is the fact that only two sets of brushes are required, while multiple-circuit windings (unless cross-connected as already explained) demand as many sets as there are poles in order to have full armature current. In most machines, however, especially for low pressures of 110 or 220 volts, it is desirable to provide the larger number of brushes to obtain sufficient area of contact for the heavy currents that are usually carried in low voltage apparatus. In such cases this advantage of two-circuit windings disappears. A prominent exception is the electric railway motor in which a

two-circuit winding is used, multiplication of brushes and danger of unequal voltages in armature circuits being particularly objectionable in this machine.

Wave and Lap Windings.—Most of the drum windings described above advance in the same direction around the armature. This is called wave-winding, because it would have that form if it were developed, that is, taken off of the core and spread out flat. It is also possible to carry the end-connections alternately forward and backward, so that the successive turns overlap each other. For example, Fig. 106 shows the development of a wave winding, a portion of it beginning with inductor No. 22 being represented by a heavy line in order to make this feature clear. A lap winding is illustrated in Fig. 108, a portion of which is similarly drawn with a heavy line.

Right- and Left-Hand Windings consist respectively of turns which pass around the core in a right- or left-hand fashion. The coils represented in Fig. 92 as passing from 1 inside, then to 2, etc., form a left-hand winding.

Double Windings.—These consist of two entirely distinct windings placed upon the same armature core, and connected respectively to alternate commutator-bars. The brush is thick enough to make contact with at least two commutator-bars, so that both windings are always in circuit in parallel. This construction reduces the tendency to sparking, because only half of the current is commutated at a time, and also because adjacent commutator-bars belong to different windings. It is also a fact that an armature coil is not likely to be short-circuited by the formation of an arc, or by copper dust, etc., on the commutator. Furthermore, an accident to one winding does not necessarily disable the machine, but reduces its current capacity. This method can be applied to any armature, and may be extended to triple or quadruple windings; its only objection is the increased number of conductors and commutator-bars, which is undesirable in small machines, but for large ones might be allowable. Nevertheless such windings are not very often employed.

Open-Coil Windings.—The windings heretofore considered have all been of the closed-coil type, in which the armature conductors are connected together and closed at the starting-point. This is the usual style of winding for direct-current machines, and is univer-

sally employed for incandescent lighting, where a steady current is desired. For series arc-lighting, however, a pulsating current is allowable, or perhaps advantageous; and armatures have been extensively used in which the winding consists of a comparatively small number of separate coils, the terminals of which are open until connected to the circuit by the commutator brushes. The Brush and the Thomson-Houston dynamos for series arc-lighting contain armatures of this kind, being the only important examples of open-coil windings, and will be considered as special types in Chapter XVIII.

Alternating-Current Armature Windings. Single Phase.—The principles and applications of alternating currents are more fully treated in Chapters VII to XI of Vol. II, but a few fundamental facts will now be noted. An elementary alternating-current generator and the curve of *E.M.F.* produced by it are represented in Figs. 84 and 85, the action having been explained in connection therewith. Any direct-current winding, except the unipolar type, can be made to yield an alternating current. Take any point of a bipolar winding, such as a Gramme ring, and follow it as it revolves; its potential is first zero, then rises to a maximum positive value after it has turned through 90°, then decreases to zero again at 180°, reaches a negative maximum at 270°, and finally returns to zero after it has revolved through a complete circle. Another point diametrically opposite to the first will pass through an exactly complementary cycle of changes, one point being positive when the other is negative, and *vice versa*. By respectively connecting these two points with two collecting-rings, on which rest two brushes that form the terminals of an electric circuit, the latter will be supplied with an alternating current.

In practice, however, alternating-current windings are usually different from those used for direct currents. One distinction is the fact that a simple open-coil winding may be, and often is, employed; but the chief difference is the intermittent action of the inductors. In a direct-current Gramme ring winding a certain number of coils are always active, while those in the space between the pole-pieces are not generating. In this way a practically steady *E.M.F.* is produced by a large fraction of the coils. But for an alternating current it is allowable to have all the coils active at one moment, and all inactive the next, corresponding to the variations in the

current. Hence, the winding need cover only as much of the armature as is covered by the pole-pieces.

Owing to the absence of the commutator, the winding of an alternator armature is somewhat simpler than that of a continuous current machine. Any of the four kinds of windings previously mentioned might be used, but the ring form is now seldom employed. The advantages of the alternating-current drum winding are the same as for the corresponding direct-current winding, and furthermore, with equivalent armatures, either toothed or smooth-core, the drum loops have less inductance than those on a ring core. In virtue, therefore, of its lower resistance and inductance, the drum type gives better regulation for constant potential service.

Figures 109 and 110 show two forms of drum winding applicable to alternating-current machinery, the coils being equal in width to the pole-pieces, and also to the spaces between the poles. All the coils are in series, and form a single open-circuit winding, terminating at the collecting-rings *R* and *T*. At the moment represented, the inductors are all generating, and the maximum *E.M.F.* is produced, *R* being positive. A rotation of 90 magnetic degrees (the distance between centers of adjacent poles being called 180°) brings the coils into the neutral spaces, and the *E.M.F.* becomes zero, and so on.

Polyphase Windings.—The use of two- or three-phase alternating currents belongs rather to electric power than to lighting; but systems of this kind are often installed for both purposes. These currents and their applications are discussed in Chapters VIII and X of Vol. II, only the general facts being given here.

A two-phase armature may be considered as a combination of two single-phase armatures; and, in fact, it usually consists of two entirely distinct windings, each having its own pair of collecting-rings. The essential feature is the fact that the *E.M.F.'s* generated by the two windings differ in phase by one-quarter of a period, or, in other words, one generates its maximum *E.M.F.* when the other is at zero. For lighting purposes the two currents are supplied to two entirely separate circuits, and each is used just as if the other did not exist. For driving motors the two circuits are combined to produce a rotary magnetic field. If either armature shown in Figs. 109 or 110 were provided with

another winding, the coils of which were placed in the spaces between the first set, the terminals being connected to another pair of collecting-rings, the result would be a two-phase armature.

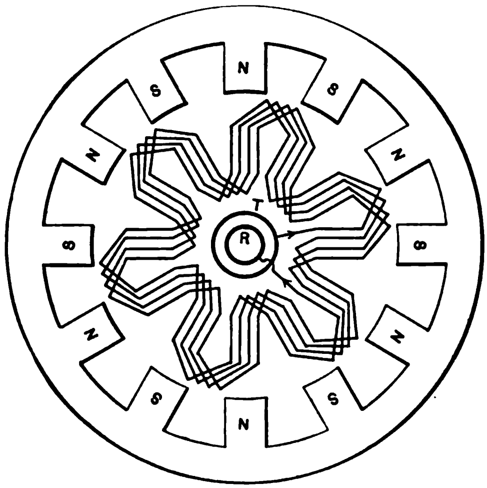


Fig. 109. Wave Type of Drum Winding for Single-Phase Alternators.

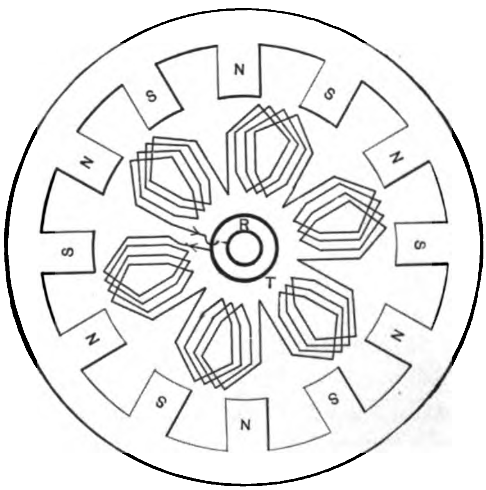


Fig. 110. Lap Type of Drum Winding for Single-Phase Alternators.

Three-phase windings are similar in principle to the two-phase, but produce three currents differing 120° in phase; and, furthermore, the three windings are connected together in either the **Y** or the △ form. In the **Y** winding the three sets of coils start at a

common point, and the three free ends are connected respectively to three collecting-rings, from which the three main conductors of the circuit lead. In the Δ winding the three sets of coils are all connected together; and the current is tapped off at the three junctions (i.e., corners of the triangle).

Alternators, whether one- two- or three-phase, are now generally made with stationary armatures and revolving fields. It makes practically no difference in the action, but allows the armature connections to be made solid, the field-current, which represents far less energy, being much more easily supplied through collecting-rings. On the other hand, the field-magnet being usually heavier than the armature, this plan increases the weight of the moving parts, which is advantageous where fly-wheel effect is desired.

Alternating-current generators have also been built, in which both field-coils and armature-coils are stationary, the lines of force from the former being caused to cut the latter by revolving pieces of iron, whic carry the lines from one set of coils to the other. These are called inductor machines, one type being the Stanley two-phase alternator. (See Figs. 151 and 152.)

Dynamotor Windings.—A motor and a dynamo are often combined to act as a transformer, as, for example, when a 500-volt direct-current motor is directly coupled to a 110-volt dynamo, the former being driven by current from an electric railway circuit, and the latter furnishing current for incandescent lamps or storage batteries. A similar combination with a generator wound for alternating currents would serve to transform direct into alternating currents, or *vice versa*.

The two functions are often combined in a single machine to secure compactness, in which case the two armature windings are put on one core, and are acted upon by the same field-magnet. Each winding is independent and complete in itself, and is thoroughly insulated from the other. Consequently, any of the forms of winding already described may be adopted, the only peculiarity being the fact that the two windings must be superimposed, or laid side by side in alternate sections. Besides the advantage of compactness secured by placing both windings on the same core, the armature reactions of the two counteract each other, so that demagnetization of the field by back ampere-turns, and shifting

of the brushes, are both avoided. Armature reaction is discussed fully later in connection with Figs. 134 to 137.

A still further simplification consists in using the same armature winding to act as a motor and as a generator at the same time. This is accomplished by connecting the winding to the sections of a commutator in the usual way, and also to collecting-rings. A direct current supplied at the commutator will cause the armature to revolve as a motor, and at the same time an alternating current may be obtained from the collecting-rings. This current will be single- two- or three-phase, depending upon the number of collecting-rings, and the points of the winding to which they are connected. For example, if an ordinary bipolar Gramme winding be connected at four equidistant points (i.e., 90° apart) to four collecting-rings, a two-phase current may be taken off from the rings. Conversely, a two-phase current fed to these rings will enable a direct current to be obtained from the commutator.

Such a machine is called a *rotary converter* or simply "rotary." The latter term is loose and converter alone is sufficient, because that name should no longer be applied to the ordinary alternating-current transformer.

A rotary converter may be used also as a *double-current generator.* All that is necessary is to drive it by an engine or turbine, and direct current may be derived from its commutator while alternating current is taken from the collecting-rings, or either may be obtained alone. The same machine may thus supply locally a low-voltage direct-current system, and through transformers a high-voltage alternating-current system at a distance. Dynamotors, rotary converters, and double-current generators are more fully treated in Chapters V and X of Vol. II.

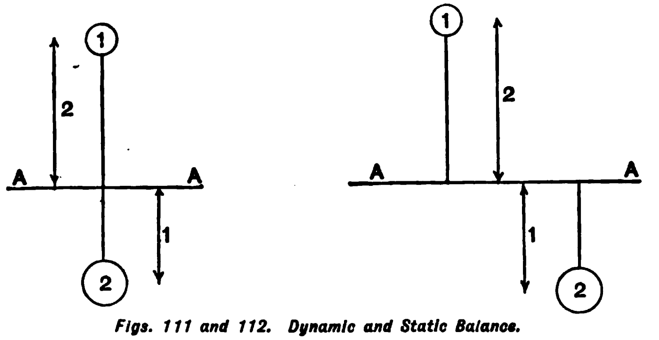
Balancing of Armatures.—A perfectly balanced armature runs so smoothly that one can hardly detect that it is moving at all; whereas the slightest excess of weight on one side is likely to cause vibration. This produces noise, and constantly jars the machine, which not only strains it, but also makes the brushes spark.

It is practically impossible to construct an armature core and winding so true that it is balanced; hence armatures are almost always balanced when they are nearly completed. The usual plan is to place the armature with the ends of the shaft resting on two Λ-shaped rails which are perfectly level. It is then rolled back

and forth until the lightest point is found by the fact that it tends to remain uppermost. A piece of lead is attached to the armature at this point, the exact amount required for perfect balance being found by trial.

Ordinarily a strip of sheet lead is used, and is held by a band of wire wound around the armature. Another arrangement consists in inserting pencils of lead in holes in the projections of a toothed armature or in the core. It is also obvious that weight may be removed from the heavy side of the armature in order to secure a balance. This may be done by boring a hole in the core, but is open to the objection that it connects the disks together and impairs the lamination. If the end core-disks have been made thick, holes can be drilled in them to obtain a perfect balance.

The question is often raised as to whether a standing balance is also a running balance. As a matter of fact, a body balanced statically is also balanced dynamically, provided the weights are symmetrical with respect to the axis of rotation. In Fig. 111 a weight of 2 lbs., at a radius of 1 foot from the axis AA, will balance a weight of 1 lb. at a radius of 2 feet, whether standing or running, because the static effect and centrifugal force are both directly proportional to the radius, and the weights are in a line perpendicular to the axis AA. In Fig. 112 the weights will still balance statically, but not dynamically, since the ends of the axis AA will be pulled in opposite directions when running. Ordinarily a weight placed in the middle



Figs. 111 and 112. Dynamic and Static Balance.

of an element of the armature will balance it sufficiently well; but if it is necessary to obtain a running balance, it may be found by revolving the armature in bearings which are mounted on springs, or by hanging up the machine, or mounting it on a wheeled truck. Weights are tried at various points until the armature runs steadily.

Binding wires are essential on smooth-core armatures to prevent the inductors from being thrown out by centrifugal force. They are also required on armatures with slots in which no provision is made for wooden wedges. Steel, phosphor bronze, or other metal with great tensile strength and poor electrical conductivity, is used; since there is a tendency for eddy currents to be set up in these bands. For the same reason a small wire about .03 to .06 inch in diameter is employed. These bands of wire are ½ to 1 inch wide, and about 3 inches apart, and are wound on strips of mica, to insulate them from the conductors. The ends of the wire are secured by small straps of thin brass folded around the band and soldered.

It is particularly desirable that the armature should lose its heat as rapidly as possible, in order to keep down its temperature, and any covering interferes with the dissipation of heat. For that reason armatures are generally left uncovered; and in most cases special means of ventilation are provided, usually in the form of openings in the armature core, as represented at *DD* in Fig. 96. A convenient way to secure these openings is to introduce plates similar to that illustrated in Fig. 113. In some cases ventilation is further increased by providing fans or wings on the armature. In armatures having slots narrower at the top or specially formed for the purpose, wooden wedges or sticks may be forced into the tops of the slots, which gives an excellent finish, and dispenses with any covering or binding-wires.

Fig. 113. Ribbed Core Plate.

Commutators.—To obtain a direct current from an armature winding we have already seen that a commutator is required. For a closed-coil winding it usually has a large number of bars, the

maximum average voltage between adjacent bars being usually limited to nineteen volts or less, while for the open-coil—Brush or Thomson-Houston—armature, the commutator has a small number of sections. The former type of commutator is composed of a number of bars of copper *B*, held together by nuts *NN*, and washers *WW*, screwed on the ends of central tube *TT*, as shown in Fig. 114. The bars are insulated from the washers by mica, as represented at *MM* and *DD*, and each bar is insulated from its neighbors by sheets of mica *E*. The bars must also be insulated from the tube *T*, either by a tube of mica *C*, or by a sufficient air-space. It is very important to have the parts of the commutator perfectly fitted together and screwed up extremely tight, in order that there shall be no interstices or looseness. The ends of the sections of winding may be connected to the projections *P*, by inserting them in the slots *F*, and firmly binding them in place by the screw *H*, as shown in the small detail view. The end of the wires and the screw *H* may then be soldered to make them still more secure, and they may be released at any time by simply applying a hot soldering-iron to them. Solder

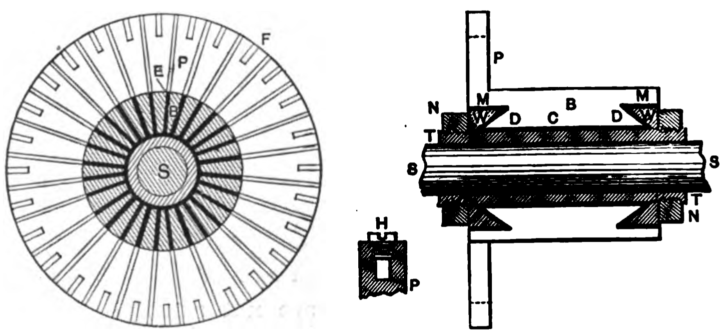


Fig. 114. Construction of Commutator.

alone is not sufficiently reliable for holding commutator connections. The mica insulation may extend outward between the projections *P*, to prevent copper dust from getting between them, or the projections may be made thinner and separated by air spaces. For example, the projections *P* may consist of strips of sheet copper set into slots in the end of the commutator-bars, and bent around the wires at the outer end. Many commutators are made with the

washers *WW* entirely outside of the ends of the copper bars, so that the effective length or face of the commutator is just that much shorter, as in Fig. 115. The undercut form of bar shown in

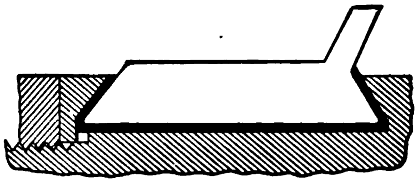


Fig. 115.

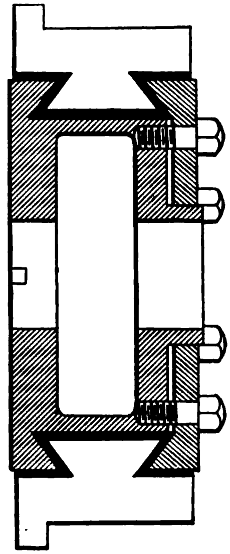


Fig. 116. Construction of Commutator of Medium Size.

Fig. 114 gives so much greater useful surface, however, that it is usually preferable. Figs. 116 and 117 illustrate different designs of clamping-rings for large commutators.

One of the best materials for commutator-bars is simple rolled copper rods of the proper cross-section, and cut off in suitable lengths, since they are tough and of uniform texture. But these cannot be made with projections such as *P*, hence drop forgings or castings are used. The latter are not usually of sufficient toughness and uniformity, and require to be annealed, rolled, or treated in some way. The use of brass, iron, steel, or other metal except nearly pure copper, has not usually resulted in success, for the reason that these metals seem to burn more than copper under the influence of sparking. Attempts to substitute other insulating materials for mica have also been unsuccessful in most cases. There are many varieties of mica differing considerably in hardness and other qualities. It is very important to select that kind which

wears at the same rate as the copper. If too hard, it will be left projecting beyond the copper and prevent the brushes from making proper contact. On the other hand mica that is too soft wears away and leaves furrows between the bars in which copper dust collects, causing short-circuits.

Brushes. — The principal kinds of commutator brushes which have been used are: —

1. A simple strip of springy sheet copper, the ends of which are slit to insure contact at several points, and set almost perfectly tangent to the commutator. These are used on the Brush and Thomson-Houston arc dynamos in which the current is limited to ten amperes.
2. A laminated brush composed of a number of strips of thin sheet copper soldered or otherwise held together at the end farthest from the commutator. These brushes are called "tangential;" but actually they are beveled off at the end, and inclined to the true tangent in order that the ends of all the sheets may make contact.
3. A laminated brush similar to the preceding, but with the sheets placed perpendicular to the axis of the commutator. The objection to this brush is the fact that it tends to wear grooves in the commutator. This brush is also placed at an inclination to the tangent.
4. A rectangular bundle of copper wires soldered together at one end. This form is likely to cause the same trouble as the last, but not to the same extent. Its position is also inclined to the tangent.
5. Sheets of fine copper gauze are folded or rolled up, and pressed into rectangular form. These brushes make a very perfect contact by reason of their soft, spongy nature, but they are quite expensive. They may be inclined to the tangent like the three preceding forms, or they may be set radially. The latter position gives the advantage that the point of contact does not change as the brushes wear away.
6. Slabs, blocks, or rods of carbon set either radially, or inclined to the tangent, usually the former. Graphite or a mixture of graphite and carbon is also used, possessing the advantage of a lower coefficient of friction, higher specific and contact resistances, and is more easily cut or fitted.

Carbon brushes tend to keep the commutator smooth, in fact, they actually polish it; whereas copper brushes tend to tear and roughen the surface. The amount of wear is also less, and a commutator will last several times as long with carbon brushes. The commutator may be reversed, and run in either direction with carbon brushes; but this advantage applies more to motors than to dynamos. Carbon dust is far less objectionable than copper dust

about an electrical machine, since it does not produce such a bad short circuit. The chief merit in carbon brushes is the reduction in sparking, which results partly from their smoothing action, and partly from the *gradual* shutting off of the current which occurs when each commutator-bar leaves the brush, owing to the higher specific resistance of carbon. Copper, on the other hand, has such a high conductivity that the full current flows to each commutator-bar, even when it has almost entirely passed from under the brush; and then it is very suddenly interrupted, causing a spark, which would not be produced if the current were gradually shifted to the next commutator-bar.

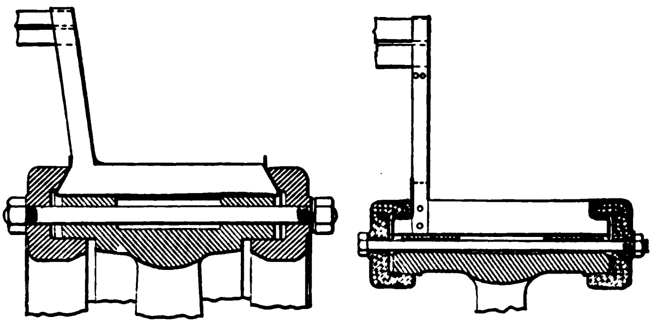
This explains the paradoxical fact that a certain amount of resistance is desirable in a brush. But as this resistance is only required in the trailing edge of the brush, attempts have been made to increase the conductivity of other portions by combining copper sheets or wires with the carbon.

In addition to the high resistance of carbon brushes, which is decidedly objectionable except in one edge, they are too easily broken, and, having no flexibility, the least roughness, vibration, or dirt will throw them out of contact with the commutator; nevertheless, they are generally preferred unless the amount of current is too great for their conductivity. The use of rollers instead of brushes to make contact with the commutator has often been tried, but has not been successful owing to the small area of contact.

The relation between pressure, contact resistance, and friction of brushes varies considerably, but average figures have been found by experience. Carbon brushes will carry about 40 amperes per square inch of contact surface. In smaller machines this may be increased to 60 or 70 amperes per square inch. Copper brushes are used at 150 to 200 amperes per square inch. The ordinary pressures are 1.5 to 2 lbs. per square inch for carbon and 1.25 to 1.5 lbs. for copper brushes. Peripheral speeds of commutators vary from 1,500 to 2,500 feet per minute, being usually greater in larger machines.

The contact resistance of brushes is not constant, varying approximately inversely as the current density. This gives a fall of potential (drop$=CR$) that is nearly the same at all loads within practical limits, being .8 to 1. volt for carbon brushes at each contact. In

practically all cases this would amount to 1.6 to 2. volts for the two contacts, positive and negative, of a machine. It is not materi-



Figs. 116a and 117. Construction of Large Commutators.

ally affected by putting a number of brushes in parallel in each set or by having several sets as in most multipolar machines, because this mereiy reduces the current density, and the contact resistance varies in the inverse ratio, their product being nearly constant, as already stated. The rise in temperature is less with a greater area of contact, and it is chiefly for this reason that brushes are added to limit the current density to about 40 amperes per square inch. The contact resistance of copper brushes is about one-twentieth of one-tenth that of carbon. The watts lost in the brushes are calculated by multiplying the total drop in volts (=1.6 to 2. for carbon) by the total current that they carry.

The coefficient of friction of brushes is about .3 for carbon and .2 to .25 for copper. The loss in watts due to carbon-brush friction is therefore:—

$$W = \frac{.3 \times 746}{33000} PS,$$

in which P is the total pressure in pounds on the commutator and S is its peripheral speed in feet per minute.

The above data, electrical as well as mechanical, assume that the commutator and brushes are in good condition. If they are dirty or rough the losses due to contact resistance and to friction are both increased, in some cases very considerably.

Brush-Holders.—The devices used for holding the brushes against the commutator with the proper pressure differ in each

type of machine, and no general rules can be laid down. The requirements to be fulfilled by a brush-holder are more numerous and difficult than one would expect. The brush must be held securely, and at the same time it must be fed forward as it wears away. It must be capable of being lifted away from the commutator, and preferably held out of contact by some form of catch. The brush should be easily removable for cleaning or renewal. The spring pressure must be adjustable.

One of the troubles with brush-holders results from the current passing through the spring, which destroys the elasticity of the latter by heating it. This may be avoided by insulating one end of the spring, or by carrying the entire current directly from the brush itself to the main conductors by a flexible copper strip or cable firmly connected to both.

The brush-holders proper are carried by a ***rocker arm*** for bipolar, and by a ***rocker ring*** for multipolar machines, which is mounted upon one of the main bearings, or upon a support specially provided for it, and is arranged to revolve concentrically with the shaft, so that the position of the brushes may be shifted back and forth until the minimum sparking is obtained.

It is also desirable to have the brush-holders capable of slight individual adjustment, that is, with respect to each other, thus enabling each to be set at its own minimum sparking-point. A form of brush-holder is illustrated in Fig. 118, other examples as

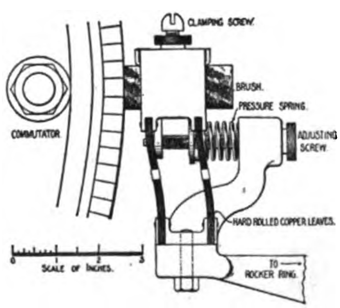


Fig. 118. Brush-Holder.

well as different styles of rocker arms and rings being represented in connection with the typical machines in Chapter XVIII.

FIELD-MAGNET CONSTRUCTION.

General Form.—The form of the field-magnet depends primarily upon whether it is bipolar or multipolar. The former was almost universally adopted prior to 1890 for all sizes of machine even up 100 kilowatts or more. Its use is now confined to small machines of less than 5 kilowatts, larger sizes being made multipolar to save material, as explained later. Bipolar field-magnets may be of the simple horseshoe type, placed as in the original Edison dynamos (Fig. 139), or may be turned with pole-pieces upward (Fig. 140), often called the "inverted horseshoe." The term *undertype* is frequently applied to the former, and *overtype* to the latter, on account of the position of the armature. Some designers have put the horseshoe form of magnet on its side, as represented in Fig. 119, but such a machine is unsymmetrical, and for that reason not particularly pleasing in appearance. Moreover, the entire base of the machine and the bearings are connected to one of the pole-pieces, and the large surface thus exposed increases the magnetic leakage.

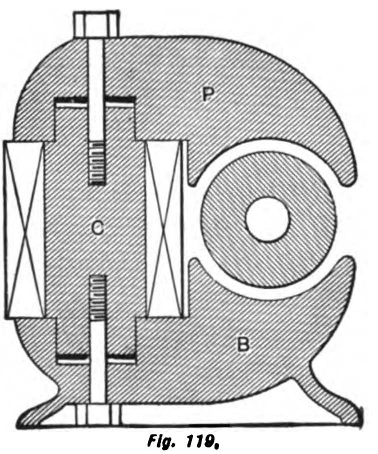


Fig. 119.
Bipolar Field-Magnet with Single Coil.

This type is interesting from the fact that it requires only a single magnetizing coil. The same form is also arranged to stand with the core *C* horizontal, the armature being either over or under the latter. In this case the bearings must be supported upon arms of brass or other non-magnetic metal, since they extend from one pole-piece to the other. This form, as well as the undertype, is open to the objection that if set upon an iron base, the latter would act as a magnetic short circuit from one pole to the other, and rob the armature of a large fraction of the flux. This difficulty was reduced in Edison undertype machines, which are no longer manufactured, by interposing thick pieces of zinc between the pole-pieces and the base; but even with this construction Hopkinson *

* Paper on "Dynamo-Electric Machinery," *Phil. Trans. of Royal Soc.*, May 6, 1886.

found the magnetic leakage through the base to be 10.3 per cent of the total flux. The other form (with single horizontal core) is ordinarily used without an iron base-plate, the pole-pieces being provided with feet, upon which the machine rests.

The overtype, on the other hand, has small magnetic leakage, because the pole-pieces are not near the base or other magnetic conductor, and their surface is less than in the undertype or in the single-coil magnet shown in Fig. 119. Fig. 120 represents a radically different form of bipolar field-magnet, commonly called the Manchester type, from the fact that machines of this kind were designed by Dr. John Hopkinson, and manufactured by Mather & Platt in Manchester, England. This construction is extremely solid; but it has the undesirable feature that there are two magnetic circuits in parallel, producing what are called *consequent poles*, and each circuit requires as many ampere-turns as a single (horseshoe) magnetic circuit. The number of ampere-turns is doubled, but each is only

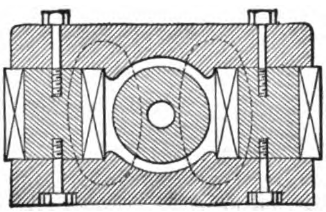


Fig. 120.
Manchester Type of Field-Magnet.

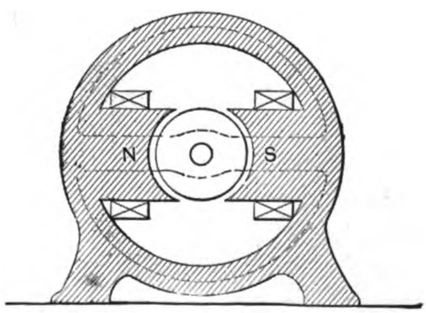


Fig. 121. Bipolar Ring Field-Magnet.

$\sqrt{\frac{1}{2}}$ times as long, because the cross-section of each core is one-half that of an equivalent single core. The required length of wire is therefore $2\times\sqrt{\frac{1}{2}}=1.41$ times as great for the double magnetic circuit. This form also has considerable magnetic leakage, the entire base and bearings being connected to one of the pole-pieces, the same as in Fig. 119.

A ring arrangement of bipolar field-magnet that may be partly

or wholly inclosed is illustrated in Fig. 121, the modern tendency being to adopt machines that are partially or completely enclosed.

Multipolar field-magnets are adopted in practically all machines, whether for direct or alternating current, excepting the small direct-current types already mentioned. The almost universally accepted form consists of an external ring with inwardly projecting cores terminating in pole-pieces, as shown in Fig. 122. This construction has the advantages of strength, simplicity, symmetrical appearance, and minimum magnetic leakage, since the pole-pieces have the least possible surface. The four-pole magnet in Fig. 123 is simple, since only two coils are required; but the entire base and upper

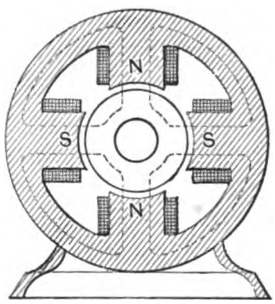


Fig. 122. Multipolar Ring Field-Magnet.

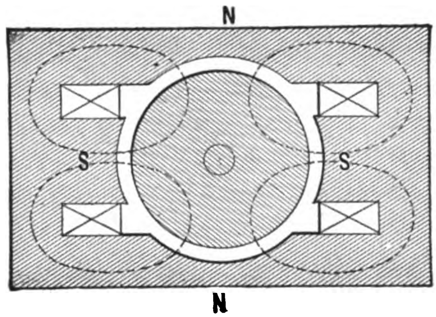


Fig. 123. Four-Pole, Two-Coil Magnet.

surface are magnetic, and the two poles N and N being indirectly magnetized, not having any coils of their own, are not as powerful as the poles S and S, so that the magnetic lines are more easily distorted in the former, which causes sparking. This construction is thoroughly compact and substantial, however, and has been used where space is limited, or where a machine is particularly exposed to mechanical injury, as in mining-work.

Material for Field-Magnets.—The principal materials utilized for the purpose are wrought iron, cast steel, and cast iron, which can be used singly or in combination.

The magnetic qualities of these materials are given in the curves in Fig. 82. Wrought iron and cast steel have the same permeability at about 15,000 lines per square centimeter, below that the former being a little superior. The objection, however, to the use of wrought iron for field-magnets is the difficulty of making in the forms required. This may be avoided by using it in simple forms, such as the plain cylinder C in Fig. 119, which can easily be made by cutting off

lengths from round bars, the latter being very cheaply manufactured in rolling-mills. To make more complicated shapes of wrought iron involves forging, which is expensive.

The cheapening and development of the process of casting "mild" steel (soft steel) with a very small amount of carbon has resulted in the general adoption of this metal for field-magnets. It combines high permeability, cheapness, strength, and the ability to be cast in any reasonable form. It is not economical to use cast iron for the *cores* of field-magnets, since it requires from 2 to 2.5 times the cross-section of wrought iron or steel for the same reluctance. With a circular cross-section this requires about 1.5 times the length of wire for a given number of ampere-turns, and the necessary weight of cast iron being 2 or 2.5 times greater, makes it clumsy and more expensive. For pole-pieces, yokes, bases, or other parts which are not wound with wire, the extra circumference is not so objectionable; and often the increased weight is positively advantageous in giving greater stability. Consequently cast iron is often used for these parts, and steel or wrought iron for the cores.

In joining cast iron to these other metals, it is hardly sufficient to butt the two together, as represented in Fig. 120, because the permeability of a given area of cast iron is only one-half as great. Hence, to secure the proper surface of contact, the pieces of steel or wrought iron should be imbedded in the cast iron by placing the former in the mold when the casting is made, or the cast iron may be bored out to receive the ends of the cores, as shown in Fig. 119. Another plan is to interpose a plate of wrought iron of larger diameter than the core, to distribute the magnetic lines. Joints in the magnetic circuit are not desirable, because they involve work in fitting them together, and may cause looseness or weakness, usually avoidable, however, with good workmanship. But the common idea that joints introduce great reluctance is not true. An ordinary joint is equivalent to an air-gap of about .005 centimeter, or .002 inch, according to Ewing,* which is practically insignificant, and does not at all warrant the making of complicated castings or forgings to avoid one or two joints in the magnetic circuit.

Size and Form of Field-Magnet Cores.—The length of cores required for a given field-magnet depends simply upon the amount

* *Magnetic Induction in Iron and Other Metals*, London, 1892, pp. 273–208.

of field-winding. The turns needed are calculated in the manner described on the next page, and the size of wire is found by the method given later. It then only remains to make the core long enough to receive those turns properly, and expose sufficient surface to dissipate the heat generated by the current and thereby prevent the temperature from becoming excessive. The last question is also discussed later in the present chapter. The cores should be made as short as possible compatible with the heating limit, in order to shorten the magnetic circuit, and reduce the cost of the machine.

The area of cross-section of the field-cores is determined by the total flux, a flux density of 13,000 to 16,000 lines per square centimeter being the usual limits for cast steel or wrought iron, and 6,000 to 7,000 for cast iron.

Having ascertained the length and area of cross-section of the core, the form is easily decided upon; because in every case it should be a *simple cylinder*, unless there is some special reason for making it otherwise.

Any departure from a circular cross-section is objectionable for the following reasons:—

1. The circle has the least circumference for a given area, even the perimeter of an equivalent square being 13 per cent longer; and a rectangle with one side three times the length of the other has a perimeter 30 per cent greater than that of an equal circle.

Assuming a circle 10 inches in diameter, its area is $\pi r^2 = 3.1416 \times 25 = 78.9$ square inches, and its circumference is $\pi \times 10 = 31.4$ inches. To have the same area a square must have its side $x = \sqrt{78.9} = 8.9$ inches, the perimeter being $4 \times 8.9 = 35.6$ inches. For the rectangle $3y \times y = 78.9$ or the shorter side $y = \sqrt{26.3} = 5.1$ inches and the perimeter is $2y + 6y = 40.8$ inches. The perimeters are 31.4:35.6:40.8 or 1:1.13:1.30.

2. It is much easier to make a cylinder, because the piece itself or the pattern for it can be turned in a lathe.

3. Cylindrical spools are more easily made than elliptical or rectangular ones.

4. The operation of winding is much more difficult with a rectangular core, since the strain on the wire is very unsteady.

5. A rectangular or even an elliptical core is much more likely to cause a short circuit between the turns of wire, because the wires are forced together at certain points and cut through the insulation.

Similar arguments apply to a core having a curved axis, that is, a ring or bow-shaped field-magnet core.

These latter are far more difficult to wind, and possess little or no compensating advantage. The shortness of magnetic circuit claimed for them is very doubtful, the actual length of core being greater than if it were straight, because the winding is not so perfect. It often happens, in the design of dynamos, that it is apparently desirable to adopt a core which is not circular in section or one having a curved axis; but it is better to change the entire design in order to avoid these forms, except, perhaps, for a special machine, to fit in a certain limited space. It is also allowable to use field-cores of rectangular cross-section when the ends of the cores form the pole faces without the addition of pole-pieces; it being usually desirable to have the pole faces rectangular.

Calculations of the Ampere-Turns Required in the Field-Coils.— The methods given for determining the flux in a magnetic circuit are often roundabout and difficult, because, as already stated in the beginning of this chapter, the reluctance depends upon the flux density; consequently, it is necessary to find or approximate the latter before the value of the reluctance can be substituted in the formula. This trouble is avoided in most cases by simply fixing the number of lines of force to be used in a given case by calculation or assumption in the very beginning. The next step is to allow a sufficient cross-section of iron to carry these lines of force, with a reasonable flux density. Knowing the latter at once fixes the value of the reluctance, and the necessary number of ampere-turns is found by solving the equation. If the particular solution is not suited to the various conditions, a slight change in the original assumptions will bring it to the proper value. The more preliminary calculations that are made, the more perfect and reliable will be the final figures; and it is always wise to make assumptions on both sides of the accepted value before being satisfied that it is the best one. The ampere-turns required for the three portions of the magnetic circuit —the field-magnet proper, the air-gap, and the armature core— are determined separately. By thus keeping these quantities independent, a change can be made in one without affecting the others. In the case of each of these parts, we have the required:—

$$\text{Ampere-turns} = \frac{10}{4\pi} \cdot N \cdot \frac{L}{A\mu} = \frac{NL}{1.257\,A\mu},$$

in which N is the total flux in lines of force in that portion of the circuit (see Magnetic Leakage on page 318), L is the mean length in centimeters of the lines in the given part, A is the area of cross-section of that part in square centimeters, and μ is the permeability of the material which may be obtained by dividing the value of B by that of H obtained from the curves in Fig. 82, provided B, the flux density, is known. The latter should be fixed in the first place as already explained, and is equal to N, the total flux, divided by A, the area of cross-section. It should also be remembered that the A.-T. per centimeter given by the curves must be multiplied by 1.257 to obtain H in $C.G.S.$ units.

The proper density to allow depends upon circumstances; but usually about 14,000 lines per square centimeter for wrought iron,

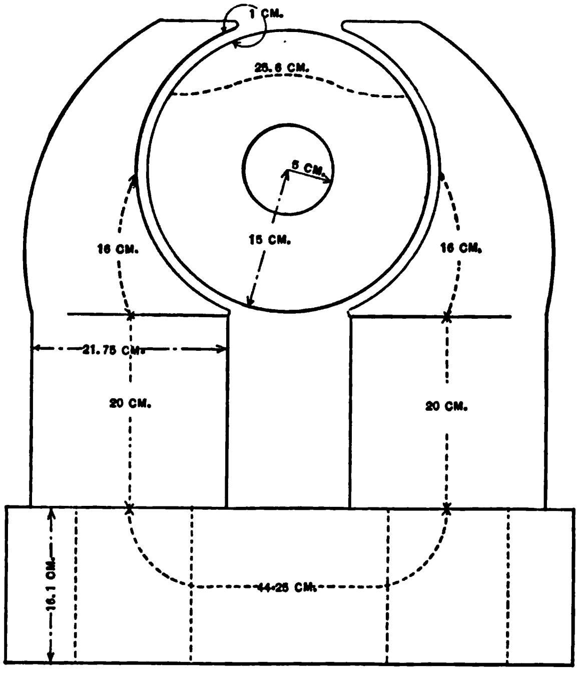


Fig. 124. Magnetic Circuit of Bipolar Machine.

or mild cast steel in the field-magnets, 10,000 to 12,000 in the armature core, 20,000 or even higher density in the armature teeth to avoid sparking, as explained under that head, and about 6,000 for cast iron, are reasonable values. The density in the air-gap is ordinarily 6,000 to 8,000 lines per square centimeter.

As already explained on page 260, it is not necessary to consider the cross-section in calculating the A.-T.'s required for a given magnetic circuit, provided its length and the flux density are known. This applies not only to a simple case with uniform material and flux density, but also to circuits composed of different materials of various sizes.

The magnetic circuit of a bipolar machine is shown in Fig. 124. It comprises an armature core, two air-gaps, and the magnet frame. The data of this circuit is as follows:—

Part.	Material.	Total Flux.	Effective Cross-section.
Armature.	Mild sheet steel	4,000,000	400 sq. cm.
Gaps.	Air	4,000,000	920
Pole-pieces.	Cast steel	5,200,000	505
Magnet cores.	Cast steel	5,200,000	371
Yoke.	Cast steel	5,200,000	650

The total flux in the magnet frame is greater by .3 than in the gaps and armature, as a coefficient of magnetic leakage of 1.3 has been assumed.

The term effective cross-section means the true conducting area. For instance, the cross-section of the armature core is 444 square centimeters but on account of armature lamination and the laminæ insulation only 90 per cent of this is iron, and therefore the effective cross-section is 90 per cent of 444, or 400 square centimeters. The effective cross-section of the air-gap is greater than the polar face (which in this instance embraces an arc of 135°) by an amount allowed for magnetic fringing. This correction is equal to the area produced by multiplying the perimeter of the polar face by .8 of the length of one air-gap. The area of the polar face is $21.75 \times \frac{32 \times \pi \times 135}{360} = 824.3$ square centimeters. The correction for fringing is $.8[(21.75+37.9)2]$, or 95.4, so that the total effective area of the air-gap is the sum of these quantities or 920 square centimeters.

The facts necessary to determine the required ampere-turns are the flux densities in the various parts, and their effective lengths. The flux densities are obtained by dividing the total flux by the area of the part in question, and the length of the magnetic path is determined by measurement.

Tabulating these results we have:—

Part.	Flux Density per Square Centimeter.	Length of Magnetic Path in Centimeters.
Armature	10,000	25.6
Each gap	4,350	1.0
Each pole-piece	10,300	16.0
Each magnet core	14,000	20.0
Yoke	8,000	44.25

By reference to the proper magnetization curves in Fig. 82, the ampere-turns per centimeter length can be determined, and multiplying these values by the total length of each part, the total ampere-turns can be readily obtained.

No curve is given for air, since its permeability is unity, and as previously explained one ampere-turn will develop 1.257 lines of force per square centimeter cross-section one centimeter long, or, if longer, inversely as the length.

Tabulating the results obtained by reference to Fig. 82:—

Part.	Flux Density.	Ampere-turns per Centimeter Length.	Total Length of Magnetic Circuit.	Total Ampere-turns.
Armature	10,000	2.0	25.6	51.0
Two air-gaps	4,350	3,461.0	$1\times 2=2$	6,922.0
Two magnet poles	10,300	4.8	$16\times 2=32$	154.0
Two magnet cores	14,000	11.6	$20\times 2=40$	464.0
Yoke	8,000	2.4	44.25	105.0
Grand total—ampere-turns				7700

These ampere-turns are equally divided between the two magnet cores.

Calculations for Slotted Armatures.—The armature in the preceding problem was assumed to be of the smooth-core type, but when slotted armatures are employed, the area of the air-gap is not simply as previously stated, because the effective area is less. In this case the air-gap area may be taken as the mean of the polar-face area and the *iron* area at the face of the teeth. The number of teeth so reckoned should be increased by one or two over the actual number under one pole, to allow for fringing, such allowance depending upon the length of the air-gap and flux density in

the teeth, the greater allowance being employed when the above factors are large.

Teeth.—The total length of tooth transversed by the armature flux is equal to twice the depth of the slot. The width of one tooth may be taken as the mean width. The number lying under one pole-piece may be taken as the number lying within the polar arc plus one or two extra to allow for fringing as previously stated. The magnetic or *iron* area of one tooth is its mean width multiplied by its effective dimension parallel to the shaft (which is the length of the armature core minus the spaces for ventilation ducts and laminæ insulation). There is still another very important point to be considered: when the teeth are worked at a flux density of 15,500 lines per square centimeter or more, part of the useful flux will pass into the core by way of the slots, because these offer a path in parallel whose magnetic permeance is comparable with that of the teeth. It follows, therefore, that the ampere-turns for the teeth calculated on the basis that they carry the total flux, will be in excess of the correct amount at high values of flux density. It is therefore necessary to determine the true value of the tooth-flux density before the A.-T.'s can be correctly determined.

A method employed by S. P. Thompson in his book on "Design of Dynamos" is as follows:

Let N_a be the flux from one pole;

N_t be the flux actually carried by the teeth;

B_x be the apparent flux density in the teeth $= \dfrac{N_a}{\text{effective tooth area}}$;

B_t be the real flux density in the teeth;

b be the mean width of a tooth;

S be the mean width of a slot;

l be the effective or *iron* length of armature core;

h be the depth of a slot;

f be the ratio between the effective and the total lengths of the armature core.

Then

$$\text{Iron section of one tooth} = bl;$$

$$\text{Air section of one slot} = \frac{Sl}{f}.$$

The total section of air-space per slot forming an alternative path in parallel for the flux is given by the area of one slot plus the

area of the insulation between laminations and ventilation ducts per tooth, or section of air-space per tooth and slot portion is

$$\frac{Sl}{f}+(1-f)\frac{bl}{f}=\frac{l(S+b-bf)}{f}.$$

Now the flux emanating from one pole-piece will be divided between tooth and air-space in inverse proportion to the reluctance of these two.

The flux in the air-space is the difference between the total armature flux N_a and the tooth flux, or (N_a-N_t).

The tooth flux $N_t \propto \frac{bl\mu}{h}$; where μ is the permeability of the toothed parts when the true flux is N_t; also

$$\text{Flux in air-section or } N_a-N_t \propto \frac{l(S+b-bf)}{fh};$$

since the path is air or equivalent to it, $\mu=1$.

Dividing the expression for N_t by that for N_a-N_t, we have

$$\frac{N_t}{N_a-N_t}=\frac{fb\mu}{S+b-bf};$$

or reducing,

$$\frac{N_t}{N_a}=\frac{fb\mu}{S+b-bf+bf\mu}=\frac{B_t}{B_x};$$

since the flux densities are proportional to the total fluxes.

A common ratio of effective or iron length to gross length for slotted armatures with ventilating ducts is .75. Substituting this value of f, we have

$$\frac{B_t}{B_x}=\frac{.75b\mu}{S+.25b+.75b\mu}.$$

To put this into practical shape, determine the values of b and s, also of B_x, and solve for B_t and μ, the value for B_t fixing that of μ, and these must be such as to satisfy the equation. Curves may then be plotted between B_x and B_t for the assumed values of b and s. A set of three such curves is given in Fig. 125, and knowing B_x, B_t can be found on the curve. If f has a value differing from .75, a new set of curves should be constructed for great accuracy.

MULTIPOLAR FIELD-MAGNETS.

While bipolar forms of field-magnets are still extensively employed for the small sizes of dynamos and motors (up to 5 H.P.), all the larger sizes are now made multipolar; hence it is advisable to consider the magnetic calculations of such a machine.

Let Fig. 126 represent a part of a modern six-pole machine, with a flux of 12,500,000 lines of force entering or leaving the armature at each field-pole. A reference to the table of leakage coefficients (page 319) gives a figure of about 1.18 for V; hence the

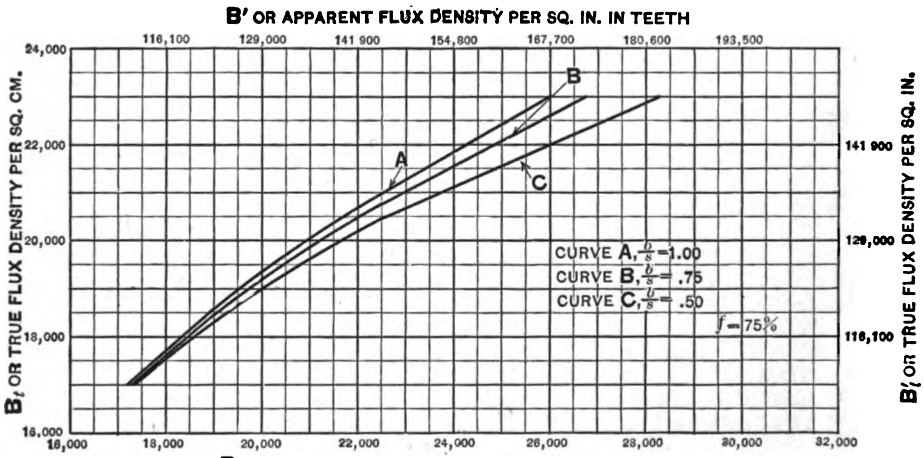


Fig. 125. Curves Showing True and Apparent Flux Density in Armature Teeth.

flux in each pole-piece will be 14,750,000 lines. The next step is to determine the magnetic areas, flux densities, and lengths.

The Yoke, consisting of cast steel, is 44.5 by 15.25 centimeters, or 678 square centimeters, in cross-section. The flux passing through the yoke from a south pole to a north pole is only one-half of that passing through the poles, since there are two parallel paths; hence the flux density in the yoke is $\frac{7,375,000}{678}$ or 10,850 lines. The length of path of the magnetic lines in the yoke is 142 centimeters by measurement.

Magnet Cores.—These consist of cast steel and are circular in cross-section, their diameters being 36.2 centimeters; hence the area of each is 1030 square centimeters and the flux desity is $\frac{14,750,000}{1030}$

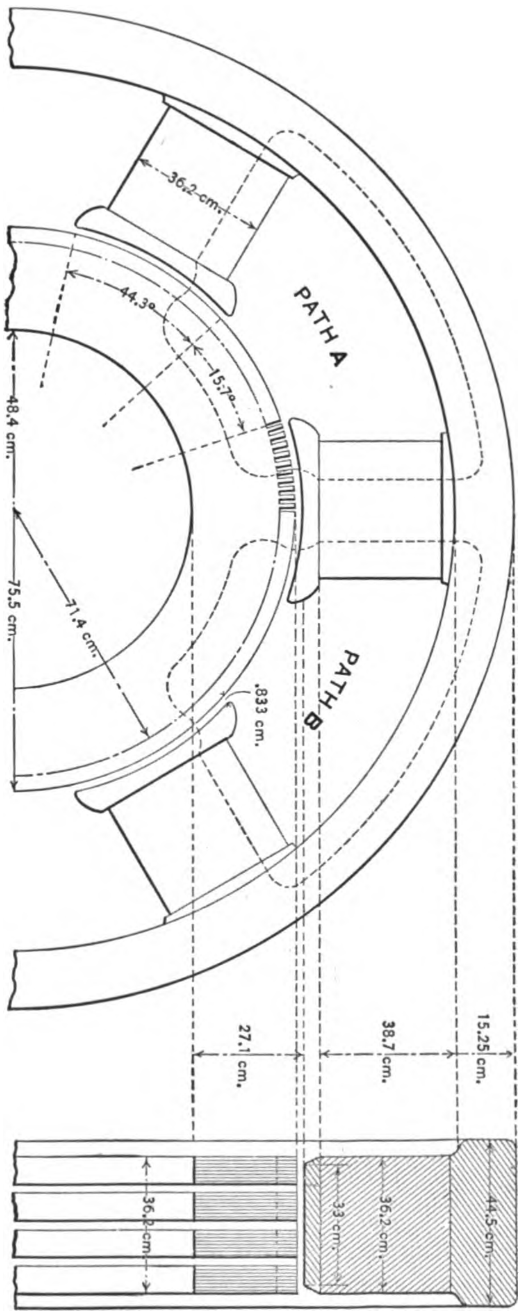


Fig. 126. Part of the Magnetic Circuit of a Six-Pole 200-K.W. Machine.

or 14,300 lines. The length of magnetic path in each core is 38.7 centimeters.

Polar Shoes.—These are cast-steel extensions affixed to the magnet cores to increase the air-gap area. The mean area of each shoe is 1,274 square centimeters, hence flux density is $\frac{14,750,000}{1,274}$ or 11,560 lines. The mean length of magnetic path per shoe is 6.9 centimeters.

Air-Gap.—Since the design under discussion is of the slotted armature type, the air-gap area is an average of the areas of the polar face and of the effective tooth surface underneath the same. Polar-face area is $76.33\times 2\pi\times\frac{44.3}{360}\times 33$, or 1,966 square centimeters. Effective tooth surface is as follows:—The armature core has 220 teeth about its circumference; hence under each pole there are $220\times\frac{44.3}{360}$ teeth, or with fringing correction this becomes 28 teeth. Now each tooth is .933 centimeter on top, and as 75 per cent of the gross length of the armature core is effective, we have area of teeth below polar face as follows:—

$$28(.933\times 36.2)\,.\,75, \text{ or } 708 \text{ square centimeters.}$$

Hence effective air-gap area is $\frac{1,966+708}{2}$ or 1,337 square centimeters; hence the flux density in the air-gap is $\frac{12,500,000}{1,344}=9,350$ lines. The length of magnetic path for air-gap is .833 centimeter.

Teeth.—The mean area of toothed portion is the mean width of a tooth multiplied by the number of teeth in each polar arc, multiplied by the effective length of the core; or in this case

$$\frac{.933+.818}{2}\times 28\times 36.2\times .75=660 \text{ square centimeters.}$$

Apparent flux density $=\frac{12,500,000}{660}=18,950$ lines. From curve *B*, Fig. 125, an apparent flux density of 18,950 lines is equivalent to a true flux density in the teeth of 18,300 lines. The length of magnetic path in teeth under each pole is 4.1 centimeters.

Armature Core.—Since there are two paths connecting N and S poles, the flux through section of armature core is 6,250,000 line. The material of the armature core is sheet steel, and its gross cross-section is 36.2×23, its effective section is $36.2 \times 23 \times .75$ or 624 square centimeters; hence the flux density is $\frac{6,250,000}{624}$ or 10,020. The length of magnetic path in the armature is 85.25 centimeters by measurement.

Tabulate the preceding data as follows:—

Part.	Material.	Effective Area in Sq. Cm.	Flux Density per Sq. Cm. or B.	Length of Path in Cm.
Yoke	Cast steel	678	10850	142.00
Magnetic core (1)	Cast steel	1030	14300	38.70
Magnetic shoe (1)	Cast steel	1274	11560	6.90
Air-gap (1)		1344	9350	0.833
Set of teeth (1).	Sheet steel	660	18300	4.10
Armature.	Sheet steel	624	10200	85.25

By reference to magnetization curves, Fig. 82, the ampere-turns per centimeter length are determined; tabulate results as follows:—

Part.	Flux Density per Sq. Cm. or B.	Ampere-turns per Cm. Length.	Total Length of Path in Cm.	Ampere-turns for Total Length of Path.
Yoke	10850	5.4	142.00	766.
Magnetic cores (2)	14300	12.8	77.40	990.
Magnetic shoes (2)	11560	6.2	13.80	86.
Air-gaps (2)	9350	7438.0	1.67	12411.
Teeth (2).	18300	126.0	8.20	1034.
Armature core	10200	2.2	85.25	173.
Grand total—ampere-turns per path A or B.				15460.

The lines in each magnetic path, for example the path A, pass through two coils so that the $M.M.F.$ of one acts in series with that of the other. Hence each coil contains $\frac{15,149}{2} = 7,575$ ampere-turns, and there are six of these coils in all.

Magnetic Leakage.—The determination of the flux in different parts of the magnetic circuit should take account of the fact that considerable magnetic leakage occurs. The exact predetermination of the amount of leakage is very difficult. The principles and methods are given by Professor S. P. Thompson.*

Experimental determinations of magnetic leakage in various forms of dynamo have been made by Hopkinson,† Ives,‡ Puffer,§ and Frisbee and Stratton.‖

The leakage coefficient v is the ratio of total flux to useful field; or, in other words, it is the number of lines in the field-magnet divided by those which pass through the armature. There is considerable magnetic leakage from the field-cores, as well as from the pole-pieces, hence the flux is not constant throughout the field-magnet. Usually the maximum flux exists in the middle of each field-coil, but often the measurement is made at the middle of the yoke. It would seem best either to take the average flux in the field-magnet in calculating v, or to find the actual flux in each part.

In calculating the ampere turns required for the field-magnet itself, it is necessary to multiply the armature flux by v in order to obtain the field flux, which in turn determines the magnetic density and reluctance in that part of the circuit.

The following table** gives the value of the coefficient of

TABLE OF LEAKAGE COEFFICIENTS.

Capacity in K. W.	Overtype $V=$	Undertype $V=$	Bipolar Ironclad $V=$	Multipolar $V=$
1–5	1.4	1.6	1.3	1.5
5–25	1.28	1.45	1.22	1.32
25–100	1.22	1.35	1.16	1.28
100–300	....	....	....	1.20
300–1000	....	....	....	1.10

* *The Electromagnet*, London and New York, 1891, p. 178; also, "Design of Dynamos," London and New York, 1903, pp. 23–27.

† *Phil. Trans. Roy. Soc.*, 1886.

‡ *Electrical World* (N. Y.), vol. xix., p. 11, 1892.

§ *Electrical Review* (Lond.), vol. xxx., p. 487, 1892.

‖ *Electrical World* (N. Y.), Feb. 16, 1895.

** "Design of Dynamo," S. P. Thompson, London and New York, 1903, p. 23.

leakage for various sizes and types of machines, the leakage being always greater with the smaller sizes of machines, cast-iron magnets, or smooth-core armatures. Any pronounced corners or projections on the frame ar likely to increase the leakage.

Methods of Field-Winding. — Having calculated the number of ampere turns required for a given field-winding, the next step is to determine how the exciting current shall be obtained. The accompanying diagrams represent the five principal methods of winding the field-magnet, *F.M.* being the field-magnet, *A* the armature, and *E.C.* the external circuit. The direction of the currents is shown in each case by arrows. The separately excited machine (Fig. 127) must be supplied with the necessary field-current from some independent source. This usually consists of a small auxiliary direct-current dynamo, whose only function is to furnish field-current to one or more machines. An alternating-

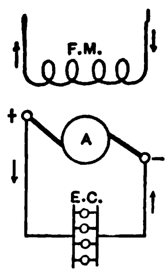


Fig. 127. Separately-excited Field.

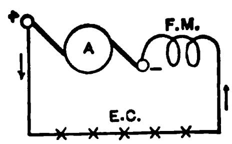


Fig. 128. Series-wound Field.

current generator is almost necessarily separately excited, its own current not being suitable for producing the field-magnetism. Self-exciting alternators have been made, however, but they really consist of a small direct-current armature incorporated with the main armature. Composite-wound alternators are also partially self-exciting, as explained later. Direct-current dynamos are often separately excited, the object being to make the regulation of the field-current more independent than is possible with a self-excitation. But this extra machine would not be ordinarily desirable except for several large generators in a central station.

The series-wound machine (Fig. 128) is the simplest possible connection; since the armature, field-coils, and line are all in series, and form a single circuit. This is applied almost exclusively to dynamos for series arc-lighting, in which the current, and there-

fore the field-magnetism, are approximately constant. Series-wound constant potential machines are also used as motors for railway and other purposes.

In the plain shunt-winding (Fig. 129), the field-coils consist of many turns of fine wire, as indicated; and only a small fraction of the current passes through them, they being in shunt connection with the armature and external circuit. This method is the one most generally used, being applied to dynamos for constant potential lighting and power distribution. Formerly it was used almost universally for these purposes, but compound winding is taking its place both for light and power. For such large electric lighting stations, where hand regulation is required constantly, the plain shunt or separately excited machine is still generally used. Plain

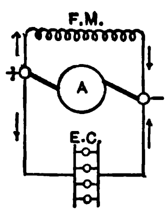


Fig. 129.
Shunt-wound Field.

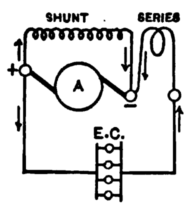


Fig. 130a.

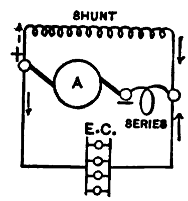


Fig. 130b.
Compound-wound Fields.

shunt-winding is also usual for constant potential motors. The two forms of compound winding (Figs. 130*a* and 130*b*) only differ in detail, and are practically the same in action. They consist of shunt-coils of fine wire, as in the plain shunt-winding; but they also have series-coils, which are made up of comparatively few turns of heavy wire carrying the main current of the machine. The direction of the series winding is such that it augments the magnetization produced by the shunt-coils, so that the greater the current drawn from the machine, the stronger the field-magnetism becomes. By properly proportioning the series and shunt-winding, a compound dynamo may be made to preserve practically constant voltage at its terminals; whereas the voltage of a plain shunt dynamo tends to fall considerably with increase of load. A still greater number of turns in the series-coils causes the

voltage to rise when the load is increased, thus making up for the drop or lost pressure on the circuits. This is called *over-compounding*, and is usually designed for a rise of 5 to 10 per cent in voltage from no load to full load.

The series-coil is sometimes arranged to oppose the magnetizing effect of the shunt-coils, this combination forming what is called *differential winding*. This has been used for motors, and is also applied to dynamos which run at very variable speed, such as those driven by windmills. In the latter case, the effect of the series-coil is to weaken the field if the dynamo runs too fast, and tends to generate an excessive *E.M.F.* The effects of these different kinds of field-winding are shown by what are known as *characteristic curves*, which represent the relation between the *E.M.F.* and the current generated by the machine. The *magnetization* curves are also useful in showing the relation between the *E.M.F.* and the ampere-turns of the field-coils.

Determination of the Size of Wire for Field-Coils. — Having calculated the number of ampere turns required, and decided upon the method of winding, the next step is to find the proper size of wire to employ. It is obvious that a given number of ampere turns can consist of a great many turns carrying a small current, or *vice versa;* and in some cases neither the turns nor the amperes are given by the conditions of the problem, but in other instances one or both may be fixed.

In a separately excited field-winding, usually the *E.M.F.* of the exciter would be given, and the selection of the size of wire would be the same problem as for a shunt-winding. If, on the contrary, the current were fixed, then the solution is the same as for series-winding.

A series-wound machine being almost invariably fed with a definite and constant current, the required number of turns is immediately found by dividing the ampere-turns by the given value of the current. The size of wire must be sufficient to carry this current without overheating. This matter of heating will be taken up presently; but as the current is practically always 10 amperes when series winding is used, the size of wire has been found by experience to be between $\frac{1}{10}$ and $\frac{1}{8}$ inch in diameter; that is, No. 10, 9, or 8 B. & S. gauge, depending chiefly upon the depth of the winding.

The determination of the best size of wire for a shunt-winding is far more difficult. The quantities which should be known are the ampere turns required, and the voltage by which the shunt-winding is supplied, i.e., that of the machine. Various methods have been given, but none are very satisfactory. One of the simplest is that suggested by F. B. Corey,* who takes the resistance of one mil-foot of copper wire at 100° F. as approximately 11 ohms. This assumption would be more correct for 98° F.; and, moreover, the allowable rise in temperature for a dynamo is 45° C., or 81° F., above that of the atmosphere, which latter we may take as 20° C., or 68° F. Hence it would be safer to assume the resistance 12.25 ohms at 65° C., as it is most important to have the machine work well at full load. This change will therefore be made in Mr. Corey's figures. The resistance of any copper conductor at 65° C. is therefore $R = \frac{12.25 \times L}{\text{Circ. mils}}$, in which L is the length of the wire in feet. The current flowing in the wire is $C = \frac{\text{Voltage} \times \text{Circ. mils}}{12.25 \times L}$. It is also evident that the ampere turns in any winding are numerically equal to the amperes that would result if a single turn of wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance, and take one-half the current, and so on for any number. Hence:—

$$\text{Ampere turns} = \frac{\text{Voltage} \times \text{Circ. mils}}{12.25 \times l},$$

where l represents the mean length of one turn in feet. By transposition we obtain the cross-section of the wire required:—

$$\text{Circ. mils} = \frac{\text{Ampere turns} \times 12.25 \times l}{\text{Voltage}}.$$

In applying the above formula to a shunt-winding for a dynamo, allowance must be made for the resistance of the rheostat, which is put in the shunt-circuit to regulate the *E.M.F.* This resistance will consume a portion of the voltage amounting to from 10 to 20 per cent. Therefore the voltage substituted in the formula should be 10 to 20 per cent lower than the *E.M.F.* of the machine.

* "A Simple Formula for Magnet Winding," *Electrical Engineer* (N.Y.), Oct. 10, 1894.

The mean length of a turn cannot be determined exactly in the first place; but it can be approximated closely, as windings are 1 to 2 inches thick for small machines and 4 to 6 inches for large ones. Usually the mean length of a turn is about 25 greater than the circumference of the core itself. A certain length and thickness coil are required to give sufficient surface to get rid of the heat, as explained later in the present chapter.

A more elaborate method is given by Mr. Harrison H. Wood.* Methods are also explained in most of the works on the dynamo.

Construction of Field-Coils.—The operation of winding field-magnets is less difficult than armature winding; the number of coils is small, the connections are not complicated, and the coils have a cylindrical or other simple form. The cylindrical form is preferable, as already explained.

It is customary to wind the field-coils on a form, spool, or frame to avoid the necessity of handling the magnet itself. This also greatly facilitates renewing the coils in case of accident or change in voltage. Wooden spools are sometimes used, but they are likely to split or chip off. One of the best forms consists of a tube of tinned iron or brass with a flange at each end against which disks of stout fiber or other insulating material are placed. The tube is also covered with two or more layers of fiber or stout paper, as the cotton covering of the wires is not sufficient to prevent "grounding" of the coils. The actual winding of the wire is a simple operation, but it should be done carefully and *systematically;* that is, as nearly as possible in the form of a perfect helix. The time saved by winding in a haphazard fashion is poor economy; wires being much more likely to become short-circuited if they cross each other at a considerable angle than if they lie parallel, because they cut through or force apart the cotton covering. It is difficult to wind fine wire in a perfect helix; but even in that case winding may advance progressively, and should not skip back and forth. In some cases, especially with heavy wires, no spool is required, the coil being wound upon a form, from which it is removed and completely covered with a wrapping of tape to hold it together and protect it, the whole being treated with varnish or shellac.

The most serious trouble in field-winding is in bringing out the

* Curves for Winding Magnets," *Electrical World*, April 27, 1895.

ends of the wire. If the inside terminal is carried through a hole in one end of the spool, it is likely to be broken by blows or frequent bending, become short-circuited by pressing against the adjacent wires, or become grounded upon the spool or magnet. It should therefore be thoroughly insulated and protected by a stout tube or a wrapping of insulating-tape. It is possible to bring both ends of the wire to the outside by making a turn of one for each layer of the other. The same result is accomplished by winding the coil in halves, the two inner ends being connected so that the other ends are outside. This complicates the winding and wires of great difference

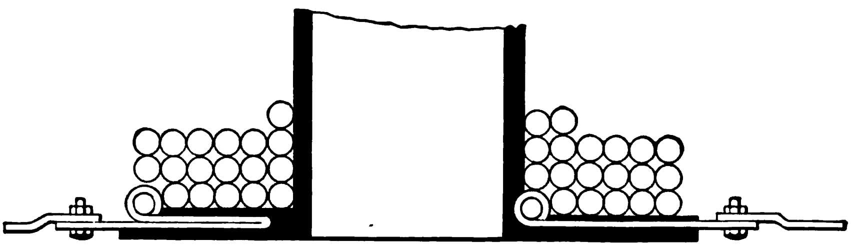


Fig. 131. Bringing Out Coil Terminals.

of potential may be brought into juxtaposition, tending to break down the insulation. Small wires must never be brought out themselves, but should have terminals of flexible cable connected to them, the latter making two or three turns around the spool before coming out. A common and reliable mode of bringing out both ends of a coil, whether of larger or small wire, is shown in Fig. 131. Two stout copper strips laid between insulating disks are connected respectively to the two ends of the coil.

The conductor in a series or compound winding has to carry the main current. Very large wires being awkward to handle, several wires in parallel may therefore be employed for these heavy currents, or ribbons of copper are used for such field-coils. The turns are insulated from one another by tape wound with the copper strip. The inside end is led out by folding it at right angles; or both ends may be brought to the outside by folding the strip in the middle, as represented in Fig. 132, and winding each half as an independent spiral. The two spirals should

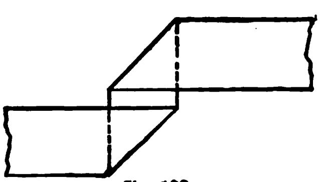


Fig. 132.

be separated by a little space, so that they may be insulated by a sheet of fiber or mica.

Dynamo Bases.—In most cases a generator is provided with a cast-iron base or bed-plate, which supports the field-magnet and bearings. It consists of a simple box of cast iron, open at the bottom, in order to give stiffness without great weight. On this base the field-magnet and bearings are firmly bolted, and it should be sufficiently rigid to stand any reasonable strain without the slightest appreciable bending.

In belt-connected machines the iron base usually rests upon a wooden *base-frame* bolted to the foundations; the former being arranged to slide back and forth on rails laid upon the base-frame, in order to regulate the belt-tension by means of screws. A direct-connected generator of small or medium size is usually bolted directly to the same cast-iron base, or sub-base, as the engine. In some cases a generator and engine are coupled together, each being complete in itself and having its own base. Very large direct-connected generators and engines may be set on separate foundations.

Dynamo Bearings and Pedestals.—These are simple mechanical constructions of ordinary form. The only peculiarities are their length, ordinarily four to six times the diameter of the shaft, on account of the high speed, and the fact that almost all generators as well as motors are provided with bearings which are self-oiling by means of rings or other devices, as shown in Fig. 133. The bearings are often made self-aligning by providing the bearing proper with an enlarged central portion of spherical shape (Fig. 133), held in a spherical seat formed in the pedestal by turning, milling, or by casting Babbitt or other fusible metal around it, thus allowing the bearing to adjust itself to the exact direction of the shaft. The upper half of the box can be taken off to facilitate renewal, etc., and to permit the armature to be removed.

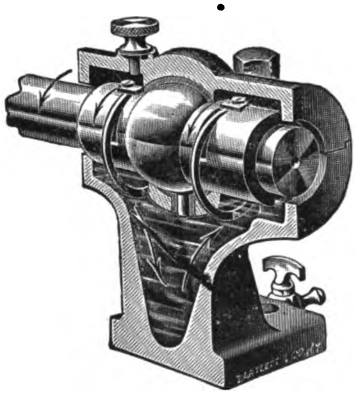


Fig. 133. Self-Oiling Bearing.

The rings shown in the self-oiling bearing revolve with the shaft, and feed the latter with oil continually, which they bring up from the reservoir below. The dirt settles to the bottom; and the upper portion of the oil remains sufficiently clean for a long time, after which it is drawn off, and a fresh supply poured in through holes provided in the top. These latter are often located directly over the slots in which the rings are placed, so that the bearings can be lubricated immediately by means of an oil-cup if the rings fail to act or the reservoir becomes exhausted.

Length of Journals.—In order to insure durability and proper operation, it is necessary in all high-speed machinery to make the journals of considerable length as compared with their diameter. The following table gives the ratio existing between journal diameters and lengths as employed in general practice:*

R.p.m.	100	200	300	400	500	700	900	1,100
$\frac{\text{Length}}{\text{Diameter}}=$	1	2	2.5	3	3.25	3.5	3.75	4.0

Bearing Friction.—The losses due to bearing friction may vary from 2 per cent in small (50 kilowatts or less) sizes to less than ½ per cent in the case of very large machines (1,000 kilowatts or over). The rate at which heat is generated in the bearings is $\text{H.P.}=\frac{fPS\pi d}{12\times 33{,}000}$; where f is the coefficient of friction, P the load in pounds on the bearing under consideration, S the speed in *r.p.m.*, and d the diameter of the journal in inches, or, expressed in watts, $W=\frac{fPd\,r.p.m.}{169}$; f varies from .04 to .1, depending upon the conditions of bearing surface.

Calculation of Heating Effects in Field-Coils and Armatures.—The design of a dynamo involves the predetermination of the temperature to which the various parts will be raised. This can only be approximate, as it depends upon many conditions, such as the location of the machine, temperature and humidity of the atmosphere, etc.; but it should be determined as closely as possible. The rate at which heat is produced in the field-coils is a

* *The Dynamo*, Hawkins & Wallis, London, 1903, pp. 324–328.

perfectly definite quantity, being equivalent to C^2R watts. This heat will cause the temperature of the coils to rise until the rate at which it is lost is equal to the rate of its production, when the temperature becomes stationary. Unfortunately, the rate at which the heat is lost cannot be accurately calculated, being dissipated by radiation, convection, and conduction, no one of which can be exactly determined.

Experience has shown that a certain rise in temperature is allowable, this being usually put at 50° C. above the temperature of the surrounding air, this being referred to at 25° C.* Tests have also demonstrated that this rise in temperature is not usually exceeded if a certain surface of coil is allowed for each watt converted into heat. This depends upon the form, position, and character of the surface. Furthermore, authorities differ in regard to what surface should be considered. In some cases only the external cylindrical surface of the coil itself is counted, in other calculations the end flanges of the coils are also included. As it is a fact that the internal surface against the core usually dissipates heat even more rapidly than the external surface,† the former should be included and the *total surface* considered. On this basis from 1 to 2 square inches of surface are required per watt lost in order to limit the temperature rise to 45° C.

The objectionable effects produced by heat in the field- or armature-coils are: First, danger of damaging or actually burning the insulation. Second, interference with the regulation of the machine; because the resistance increases .4 per cent for each 1° C. rise in temperature, which would have the effect of considerably reducing the field-strength of a shunt dynamo. Third, this rise in resistance increases the loss of energy due to the C^2R effect in all the conductors, and thereby lowers the efficiency. Fourth, expansion due to the heat might cause trouble in the bearings or other parts of the machine.

The calculation of the armature temperature is even more difficult than that of the field, more factors being involved. Heat is produced not only by the C^2R effect in the armature conductors,

* Standardization Report, *Trans. Amer. Inst. Elec. Eng.*, vol. xix. (1902), pages 1075–1091. Given in full as an appendix in Vol. II. See also under Heating in Chapter XIX of the present volume.

† *Electrical World*, July 13, 1901, p. 56.

but also by eddy currents and hysteresis in the armature core. Heat generated in the commutator and bearings may also produce considerable effect. The following expression gives the loss due to eddy currents in laminated armature cores:—

$$\text{Watts lost per cubic inch} = 40.64 \times n^2 B^2 t^2 \times 10^{-12},$$

in which n is the frequency or number of pairs of poles passed per second, B is the flux density in lines per square inch, and t is the thickness of the plates in inches. The eddy-current loss is proportional to the squares of the speed, flux density, and the thickness of a plate, as shown in the formula.

The calculation of hysteresis has been considered in the beginning of this chapter. Knowing the flux density in the armature core, reference to the curve in Fig. 83 gives the loss in watts per cubic inch. This constant multiplied by the number of cubic inches of iron in the armature core is the loss per cycle. Finally, multiplying by the frequency gives the hysteresis loss in watts.

Eddy currents and hysteresis are best determined by actual test of the completed machine, their combined effects being called *core losses*. They can be separated, however, by running the armature at two different speeds; eddy currents being proportional to the square, and hysteresis to the first power of the speed. If W_1 is the loss due to both at the speed S_1, and W_2 at the speed S_2, x the hysteresis, and y the eddy-current loss at speed S_1, then,—

$$W_1 = x + y \quad \text{and} \quad W_2 = \frac{S_2}{S_1}x + \left(\frac{S_2}{S_1}\right)^2 y,$$

from which, by eliminating x, we have

$$y = \frac{\frac{S_1}{S_2} \cdot (W_2 - W_1)}{\frac{S_2}{S_1} - 1} \qquad \text{and} \qquad x = W_1 - y.$$

It is customary to allow a certain surface per watt lost in the armature. The dissipation of heat is dependent upon the size and form of the armature, the ventilating effect due to speed, and other practical

conditions. The temperature rise θ_a in degrees centigrade of an armature in which W_a total watts (iron and copper losses) are being wasted, can be estimated by the formula

$$\theta_a = \frac{W_a}{A} \times \frac{a}{1 + (b \times v)},$$

in which A is the cooling surface of the armature, the internal surfaces being often omitted, and v is the peripheral velocity in feet per minute. In most machines the constant a is between 50 for well-ventilated armatures, and 90 for those with less ventilation. Similarly the constant b varies from .0008 to .0004.

Heating and its effects, when due to some defect or accident, are considered under Diseases of Dynamos, Chapter XIX.

The rough rule that wires for field winding should have a cross-section of about 1,200 circular mils per ampere for small machines, 1,500 to 2,000 for large ones, and armature conductors 600 to 900, is usually approximately correct, providing the thickness of winding is moderate. It serves at least as a guide until the more exact size can be determined by the methods given above, in which the surface is considered.

Armature Reaction.—The principles of the magnetic circuit and the method of calculating the ampere-turns required to produce the necessary flux have been given, but the effect of the field-magnet alone was considered. When an electric generator is doing work, the total current flows through its armature coils, setting up a $M.M.F.$ in addition to that of the field and tending to produce a corresponding flux. This phenomenon is called ***armature reaction*** and plays an important part in the action of the machine.

The conditions are shown diagramatically in Figs. 134 and 137, which represent an armature A of a dynamo and a field-magnet of horseshoe form, but only the pole-pieces S, N, and the two field coils BB and CC are illustrated. The field and armature windings are indicated in section by circles, being marked + when the current flows *toward* the observer, − when it flows away from him, and left blank when carrying no current. In Fig. 134 the field is supposed to be separately excited to full strength and there is no current in the armature. The flux represented by dotted lines is in this case quite uniformly distributed in the pole-pieces, air-

gaps, and armature core. If, now, the field-circuit be opened and a current be supplied to the armature equal to that generated by it at rated load, a *M.M.F.* will be set up and a flux produced as indicated by dotted lines in Fig. 135. This armature *M.M.F.* and flux are at right angles to those due to the field, because the current enters and leaves the armature at the points N' and S' midway between the pole-tips. The result is that current flows toward the observer in all of the left-hand half of the armature and the other way in the right half, tending to produce a north pole at N' and a south pole at S'. In fact these poles actually exist and manifest

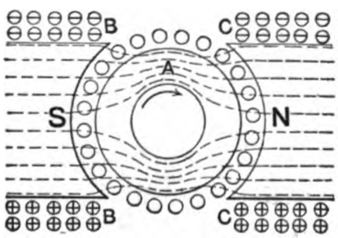


Fig. 134. Flux Due to Field Alone.

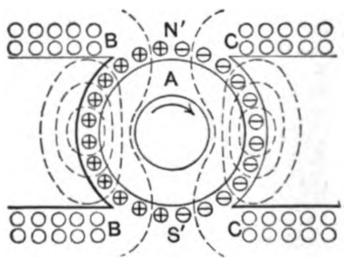


Fig. 135. Flux Due to Armature Alone.

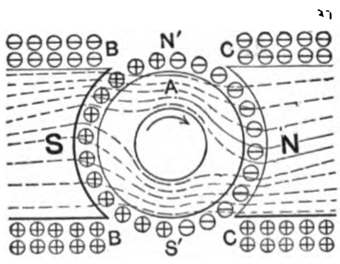


Fig. 136. Flux Due to Field and Armature.

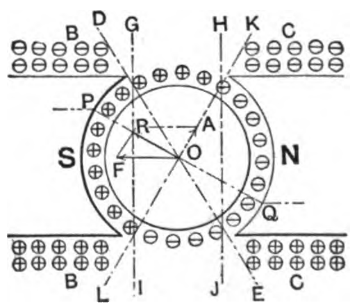


Fig. 137. Back and Cross Ampere-Turns.

themselves strongly when tested with a magnetic needle or a piece of iron, the field circuit being open as stated.

When a dynamo is generating current the field *M.M.F.* and armature *M.M.F.* both exist at the same time and a resultant flux is produced, as represented in Fig. 136. This flux is distorted in two respects: first, it is oblique, and second, it is crowded together at one of the S pole-tips and at the opposite N pole-tip. Such

distortion results naturally if the magnetic conditions in the two preceding cases are combined. The crowding of the lines at two of the four pole-tips may be simply explained by considering that there is a strong magnetic attraction between the field pole S and the armature pole N', also between N and S', so that the lines are most dense at these points. Conversely they are scattered between N and N' and between S and S', because there is repulsion with like poles. Stated more scientifically, the magnetic difference of potential and the flux density are greater between S and N' than between S and S'.

The obliquity of the flux resulting from armature reaction requires the brushes to be shifted in order that they shall be at the neutral points. Assuming that the proper position for the brushes is at right angles to the general direction of the lines of force, as is the case for a Gramme ring, then they should be placed in a vertical line passing through the center of the armature in Fig. 134, the flux being horizontal with no current in the armature. When the armature current flows and the flux becomes oblique, as explained in connection with Fig. 136, the line through the brush contacts, called the *line of commutation*, should be shifted until it is practically perpendicular to the flux.

These relations are shown by vectors in Fig. 137*a*, the line OF

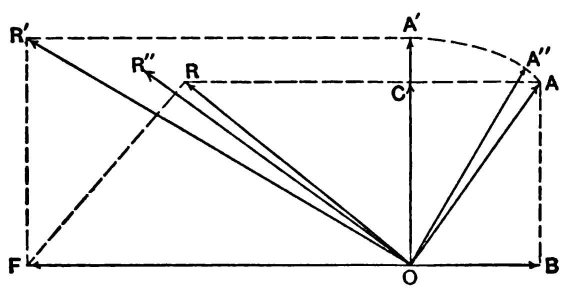


Fig. 137a. Magnetic Relations in Armature.

representing in value and direction the $M.M.F.$ due to the field magnet and the line OA' the armature $M.M.F.$ with the brushes in a vertical position. In this case OR' is the resultant $M.M.F.$, and, the flux produced being parallel to it, the brushes should be

shifted to the line OA'' perpendicular to OR'. The armature component of $M.M.F.$ also shifts to this direction, but its magnitude OA'' is unchanged because the ampere-turns remain the same. This will produce a new resultant OR'', and the brushes should be further shifted until the line of commutation OA is approximately perpendicular to OR, the final resultant $M.M.F.$ These conditions are also represented in Fig. 137, OF being the field $M.M.F.$ and OA the armature $M.M.F.$ with the brushes shifted. The $M.M.F.$ resultant is OR and the main line of flux PQ is an extension of it.

Cross and Back Ampere-Turns.—It will be noted in Figs. 137 and 137*a* that the $M.M.F.$ resultant OR not only differs from OF, the field $M.M.F.$, in direction, but is also considerably less in magnitude, because of the opposing effect of OA, the armature $M.M.F.$ The latter may be resolved into two components, one of which, OB, directly opposes the field $M.M.F.$, and the other being at right angles merely distorts the flux. The armature conductors are divided in two parts by the line of commutation LK, one half carrying current toward, and the other half away from, the observer. Another line DE is drawn through the armature center, making an angle with the perpendicular equal to that made by LK. Two vertical lines GI and HJ are drawn through the intersections of DE and LK with the armature periphery. Considering only the conductors included between these vertical lines, it is seen that they form a magnetizing coil directly opposed to the field coils BB and CC; consequently they are called *back ampere-turns*, and the flux obtained is due to the difference between the field ampere-turns and these back ampere-turns. The other conductors to the left of GI and to the right of HJ constitute a coil whose $M.M.F.$ is at right angles to that of the field and back ampere-turns, and for that reason are called *cross ampere-turns*. Their effect is to distort the flux and alter its direction, as already explained. Comparing Figs. 137 and 137*a*, it is evident that the back ampere-turns between the lines GI and HJ in the former are proportional to and may be represented by OB, the counter $M.M.F.$ in the latter; similarly the cross ampere-turns outside of GI and HJ may be represented by OC, the cross $M.M.F.$ In most machines the back ampere-turns are from 20 to 35 per cent of the total ampere-turns

on the armature, the remainder being cross ampere-turns. Hence it is necessary to increase the field ampere-turns by the amount of these back ampere-turns.

The actual polarity of the field magnet and of the armature may be ascertained by the ordinary rule that the direction of the current is counter-clockwise when the north pole of a magnet is turned toward the observer. The relative polarity in all cases is easily determined, the poles of a generator armature being near the tips of the pole-pieces toward which it is revolving, and each armature pole has the same sign as that of the neighboring field pole. The latter fact is evident when it is considered that in the case of a generator the rotation of its armature is resisted by magnetic repulsion. On the other hand, the repulsion tends to make the armature of a motor revolve, the poles of the armature being near the pole-tips away from which it is turning and having similar polarity. There is also magnetic attraction existing between the armature poles and the other pole-tips which opposes the rotation in a generator and assists it in a motor. This is not given as the best way to regard the action of these machines, but it serves to determine the position of and relation between the magnetic poles of the armature and field. It is more correct to consider the negative torque or opposition to rotation of a generator and the positive torque of a motor as being due simply to the force exerted between a magnetic field and an electric current, so that the polarity developed may be regarded as incidental.

The Principles upon which Sparking Depends.—The most important precaution in regard to direct-current generators or motors is the avoidance of sparking at the commutator. There is no trouble in preventing sparking so long as a machine is lightly loaded; but as soon as the current approaches its full value, the tendency to sparking increases, and to avoid it certain conditions are required in the design of the machine. There are also many causes of sparking, due to some defect, or to improper working of the machine; but these will be considered under Diseases of Dynamos, Chapter XIX, confining our attention for the present to those actions which depend upon the original design.

Fig. 138 represents a portion of a ring armature at the instant when the +brush *B* is touching the two commutator-bars 1 and

2. The coil F is now short-circuited and the currents from the two sides of the armature flow out from the coils E and G into the brush B, as represented by the two solid arrows. The next moment the commutator-bar 2 will leave the brush B; and the current will then be obliged to pass through the coil F, as indicated by the dotted arrows. It will require a certain time for this current to establish itself in the coil F, due to the self-induction of the latter; and during that time an arc will be formed between the brush B and the bar 2 by that portion of the current which does not pass through the coil F. This tendency to sparking being caused by the self-induction of the coil, each section should have as few turns as possible. To obtain a high $E.M.F.$, however, the total number of turns of wire must be large; and it is not practicable to have more than a certain number of commutator-bars and sections of winding.

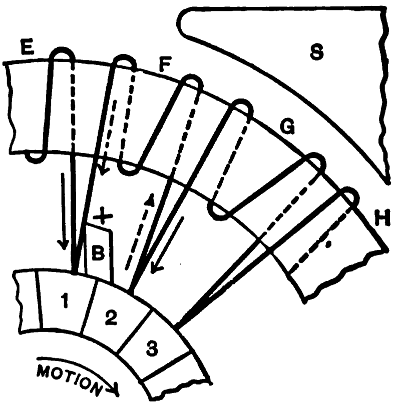


Fig. 138.
Principles upon which Sparkling Depends.

Fortunately the sparking can be avoided by the action of the machine itself. If the position of the brush B is such that the coil F is just coming under the influence of the pole-piece S, then a certain small $E.M.F.$ will be generated in it, and a current will flow through it, because it is short-circuited by the brush, as represented. The direction of this current will be that indicated by the dotted arrows; and if its value is equal to the current in the coil G, there will be no self-inductive effect, or tendency to sparking, when it is introduced into the circuit by the commutator-bar 2 passing from under the brush, since there is no change in the electromagnetic conditions. To avoid sparking, therefore, the small $E.M.F.$ generated in the coil F should be just sufficient to produce the proper "current for reversal" through its comparatively low resistance. This result is secured by shifting the brush forward (i.e., in the direction of rotation) until the short-circuited coil is brought under what is called the "fringe" of lines of force issuing from the edge of the pole-piece. A precisely corresponding action takes place at the other brush,

or brushes, of a bipolar or multipolar machine. The reason for shifting the brush forward is apparent when it is considered that the current generated in the short-circuited coil must be in the same direction as that in the coils ahead of it, because it is about to be thrown into circuit with them. In a motor the brushes are shifted backward because the armature current is reversed with respect to that of a generator having the same direction of field magnetism. It appears, therefore, that the shifting of the brushes to obtain current for reversal is in addition to that demanded by armature reaction. In other words, the ***positive angle of lead in a generator*** and the ***negative lead in a motor*** correspond to the sum of the two effects in order to have minimum sparking.

It is evident that when the armature current is increased, the current for reversal must increase to the same extent, and the brushes should be shifted still farther forward in a generator. It has been explained under the head of armature reaction that the neutral points also move forward with increase of armature current, which would be another reason for shifting the brushes with variations in load. This is so objectionable, however, that commercial machines are carefully designed to avoid it: by limiting the self-induction of the armature sections; by making the field *M.M.F.* strong compared with that of the armature; and by the use of carbon brushes which secure "forced commutation," their high resistivity having the effect of gradually introducing current into the short-circuited coil, as explained under the head of carbon brushes. Self-induction of the armature coils is reduced by making the slots wide compared with their depth, by placing few turns in a slot, and by arranging them so that their mutual induction tends to decrease the sparking.

It is obvious from Fig. 137*a* that the angle *ROF*, through which the flux is distorted, is equal to the angle *A'OA*, through which the brushes are shifted, and that both of them may be reduced by making *OF* the field *M.M.F.* large with respect to *OA* the armature *M.M.F.* In this way we obtain what is called a "stiff field," that is strong enough to prevent armature reaction from having too much effect. It is possible thus to design machines with little or no sparking, even when greatly overloaded, but the cost of the field magnet would be excessive. In practice a compromise is usually adopted; the field *M.M.F.* at the air-gaps being made 10 to 30 per cent greater

than the armature *M.M.F.** It is evident that only the portion of the field *M.M.F.* at the air-gaps is effective in controlling armature reaction, the rest being used up in overcoming the reluctance of the iron parts of the magnetic circuit. Hence the component *OF* in Figs. 137 and 137*a* represents this effective *M.M.F.*, and its value is equal to the total field *M.M.F.*, less the amounts required for the field magnet and the armature core. Usually the air-gap *M.M.F.* is from 75 to 85 per cent of the total *M.M.F.* of the field winding. Consequently the ampere-turns on the armature in most cases should not be more than 50 to 75 per cent of those on the field.

This limitation may be expressed in another way, by stating that the flux density in the air-gap should be about 100 times the ampere-turns per inch of armature periphery. Usually the former is 40,000 to 60,000 lines per square inch, so that the latter should not ordinarily exceed 400 to 600 ampere-turns, otherwise the armature current is likely to distort and weaken the flux excessively, thus producing sparking at the brushes.

Various special methods have been devised to compensate for armature reaction, such as that developed by Professor H. J. Ryan,† which consists in providing the machine with "balancing coils" that have the same number of turns, and carry the same current, as the armature conductors, but are opposite in their magnetizing effect, thus neutralizing the armature reaction. This and other devices, such as auxiliary reversing magnets and the Sayers winding, are treated by Professor D. C. Jackson in his *Text-Book on Electromagnetism and the Construction of Dynamos.* The use of carbon brushes reduces the tendency to sparking, by gradually starting the current in the short-circuited coil, owing to the considerable resistivity of the brush, as already explained under the head of carbon brushes.

Methods of Regulating Dynamos.—The *E.M.F.* of a shunt or a separately excited generator can be very perfectly and conveniently governed by inserting a rheostat or variable resistance in circuit with the field winding. By increasing or decreasing this resistance the field-current, and therefore the *E.M.F.*, are reduced or raised. This resistance is usually controlled by hand; but it is also operated automatically by electromagnetic devices which keep

* *Electric Generators*, by Parshall and Hobart, p. 117.

† "A Method for Preventing Armature Reaction," *Trans. Amer. Inst. Elec. Eng.*, vol. xii., March, 1895; also *Electrical Engineer*, Dec. 25, 1895.

the voltage approximately constant in spite of variations in load, temperature of shunt winding, etc. (See Vol. II, p. 57.)

The shunt coils of a compound-wound dynamo are regulated in the same manner as in a plain shunt machine. The series coils act automatically to increase slightly the flux and *E.M.F.* in proportion to the load or current.

The current of the constant-current dynamos used in series arc lighting is governed by special regulators adapted to each particular type, being described in Chapter XVIII.

An interesting method of regulating a constant-current dynamo consists in driving it by a steam-engine having no speed-governor. If the steam pressure and current generated by the dynamo are properly adjusted to each other in the first place, then the current will be kept constant so long as the steam pressure does not vary, for the reason that any increase in current will cause a slowing down of the engine, and *vice versa.* The combination of the two machines is therefore self-regulating, and the engine-governor as well as the dynamo-regulator are both eliminated.

The general subject of direct and alternating-current regulation, including special devices such as boosters, is fully treated in Volume II under Electrical Distribution, where it naturally belongs.

The Insulation Resistance of Armature and Field Windings.— The current carried by the armature or field conductors should never be allowed to pass into the cores, not only because of loss of energy, but to avoid the complete breaking down of the insulation, which would be almost certain to occur if a leak is allowed to exist. In the case of high-tension machines it is imperative to have the conductors perfectly insulated from the frame of the machine, to avoid the danger of shock to those who tend it. Therefore, a certain minimum insulation resistance should be maintained between the conductors and the cores or frame. The insulation resistance tests should, if possible, be made at the pressure for which the apparatus is designed. The insulation resistance of the completed apparatus must be such that the rated voltage of the apparatus will not send more than $\frac{1}{1,000,000}$ of the full load current through the insulation. When the value found in this way exceeds 1 megohm, 1 megohm is sufficient.*

* Standardization Report, *Trans. A. I. E. E.*, vol. xix., May–June, 1902.

Besides the mere insulation resistance, it is necessary to consider the point at which the insulation will break down entirely. A test might show, for example, an insulation resistance of 10 megohms, but it might be punctured and destroyed if 500 volts were applied to it. It is, therefore, necessary to make a "break-down test" also at a potential from two to five times the voltage for which the machine is intended. The Standardization Committee of the A.I.E.E. in their report suggested the following "break-down test" voltages: *—

Rated Terminal, Volts.	Rated Output.	Test Voltage A.C.
Not exceeding 400 volts	Under 10 Kw.	1,000 volts.
Not exceeding 400 volts	10 Kw. and over.	1,500 "
400 and over, but less than 800 volts	Under 10 Kw.	1,500 "
400 and over, but less than 800 volts	10 Kw. and over	2,000 "
800 and over, but less than 1,200 volts	Any	3,500 "
1,200 and over, but less than 2,500 volts	Any	5,000 "
2,500 and over, but less than 10,000 volts	Any	Double the normal rated voltages.
10,000 and over, but less than 20,000 volts	Any	10,000 volts above normal rated voltages.
20,000 and over	Any	50% above normal rated voltages.

The voltage required to break down cotton- and silk-covered wires, fibres, mica, etc., has been investigated by Canfield and Robinson; † the data in regard to the latter materials have also been determined by Steinmetz ‡ and others.

The effect of moisture on insulation resistance has been studied by T. T. P. Luquer, § and the effect of temperature by F. C. Reeve. ‖

* Standardization Report, *Trans. Am. Inst. E. E.*, May–June, 1902, vol. xix.

† *Electrical Engineer*, March 28, 1894.

‡ *Trans. Am. Inst. Elec. Eng.*, vol. x., p. 85, 1893.

§ *Electrical Engineer*, Dec. 28, 1892.

‖ *Elec. Power* (N. Y.), June, 1895.

CHAPTER XVIII.

TYPICAL FORMS OF GENERATOR FOR ELECTRIC LIGHTING.

THE types of generator used in electric lighting are so numerous, and are modified so frequently, that it is useless to attempt to describe all of them. Moreover, the principles laid down in the preceding chapter are intended to enable one to understand and judge any particular form on its merits. An examination of the machines themselves is by far the best way to compare them; and next to that the most definite and complete information regarding the different forms can be obtained from the catalogues of the various manufacturers.

Certain types, however, are so important and interesting that they deserve a description which will also be of assistance in studying other forms.

The various electric generators may be divided into the following classes:—

A. Direct-Current Machines.

1. *Constant-potential for lighting, power, railway, and electro-chemical purposes.*
2. *Closed-coil, constant-current for arc lighting.*
3. *Open-coil, constant-current for arc lighting.*

B. Alternating-Current Machines.

4. *Single-phase, constant-potential for lighting and other purposes.*
5. *Polyphase, constant-potential, for lighting, power, and other purposes.*

DIRECT-CURRENT, CONSTANT-POTENTIAL GENERATORS.

This is the most common form of generator, since it is used for incandescent lighting in nearly every isolated plant and in a large number of central stations. The current generated by it is also suitable for constant-potential arc lighting, electric motors, electric

heating and cooking apparatus, storage batteries, electrochemical and electrometallurgical purposes, etc.

The armatures of these machines are provided with closed-coil windings of either the drum or ring type. The field-magnets are usually either shunt or compound wound, but in some cases are separately excited. They are bipolar or multipolar in form, resulting in considerable differences in design and appearance; the former will be considered first.

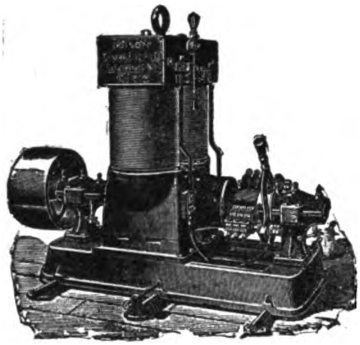


Fig. 139. Edison Bipolar Dynamo.

The Ediscn Dynamo is historically the most prominent example of this class. It consists, as shown in Fig. 139, of a horseshoe (undertype) field-magnet, and a smooth-core drum armature. The pole-pieces are magnetically separated from the base by zinc castings.

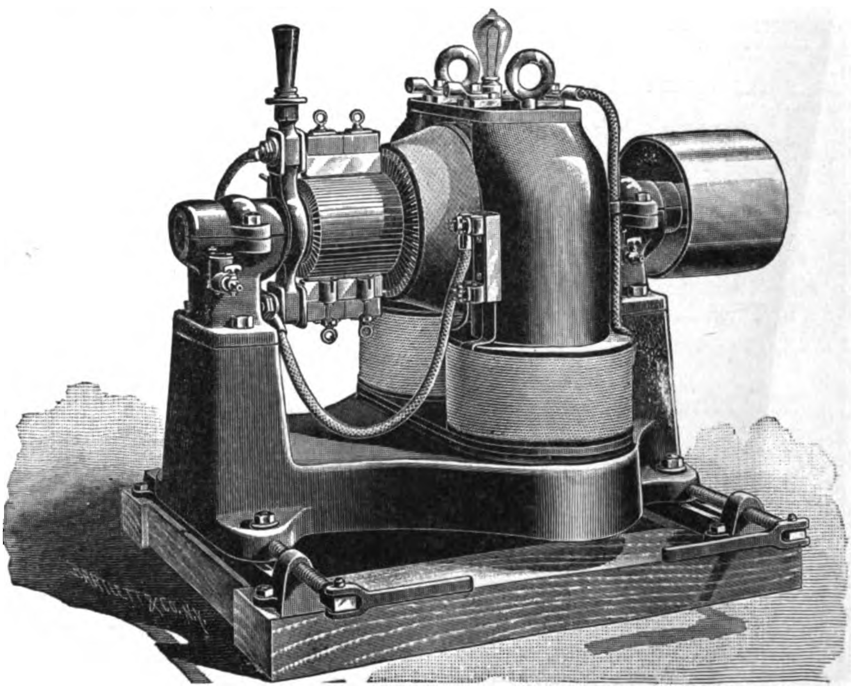


Fig. 140. The Crocker-Wheeler Bipolar Dynamo.

This type was formerly employed in nearly all low-tension incandescent-lighting central stations and isolated plants, but is no longer

manufactured, having been replaced by multipolar machines for direct coupling with engines. It is simple, substantial, and symmetrical in appearance; but considerable material is saved by adopting more modern designs.

The Crocker-Wheeler Bipolar Dynamo, as shown in Fig. 140, consists of a horseshoe (overtype) field-magnet and a slotted ring armature. The field-magnets are either drop-forgings of wrought iron, or steel castings set into a cast-iron base. This type in the smaller sizes from $\frac{1}{6}$ to 5 kilowatts has been made in large numbers, but is being superseded in many cases by the inclosed bipolar form (Fig. 121). Larger machines are multipolar.

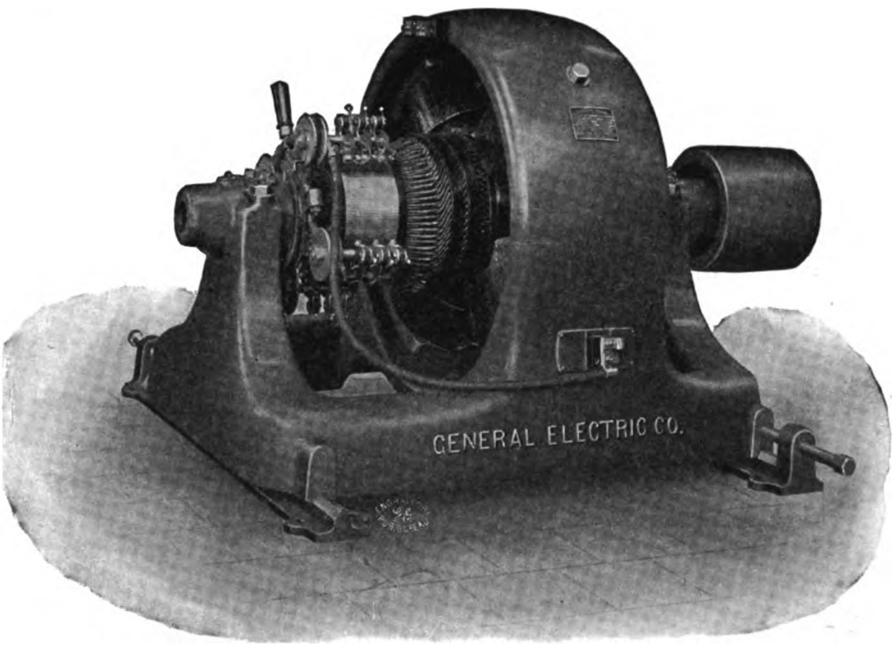


Fig. 141. Belt-Driven Generator.

Multipolar, Direct-Current, Closed-Coil Dynamos.—The general form of multipolar dynamo shown in Fig. 141 has been adopted almost universally, being manufactured by the General Electric, Westinghouse, Crocker-Wheeler, Bullock, and other companies in the United States, as well as by the Allgemeine Elektricitäts Gesellschaft of Berlin, the Oerlikon Works, Brown, Boveri

& Company of Switzerland, and by other manufacturers in Europe.

The field-magnet ring is almost always circular. The advantages of this form of magnet are great mechanical strength, easy construction, compactness, symmetry, effective position of coils, short magnetic circuits, small magnetic leakage, owing to pole-pieces having minimum surface, and upper half of magnet is easily removed to give access to the armature. Machines of any size and number of poles have the same general design, not only for direct, but also for alternating, currents; and either the drum or the ring form of armature may be adopted, usually the former.

Multipolar Generators for Direct Connection with Engines.—For many installations, direct-driven generators differ from belt-driven machines. They require less floor space owing to the absence of the belt, which means a saving in investment for real estate and buildings. Their efficiency is higher, due to the absence of belt and

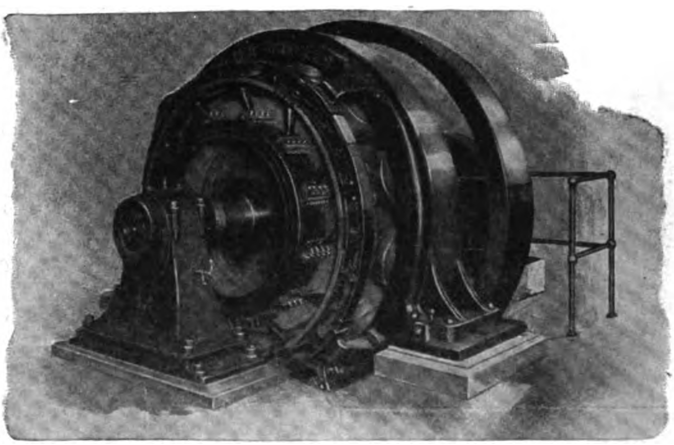


Fig. 142. Direct-Connected Generator.

counter-shafting losses, and the absence of belt noise allows these machines to be operated where belt-driven equipments would not be considered. The general design of direct-driven generators is shown in Fig. 142, being very similar to that of the ordinary belt-driven types. The chief modifications are the greater number of poles and the larger diameter of armature, necessitated by the smaller number of revolutions per minute, thus keeping the peripheral

speed about the same. The various electrical manufacturing companies build direct-driven generators, similar in appearance and efficiency. The capacities for small equipments are in general accordance with the standard sizes given on page 178, as recommended by the American Society of Mechanical Engineers.

The concentration of generator capacity into as few units as the station load will permit has long been recognized as a requisite to economical operation. Accordingly machine manufacturers are now making generator units up to 5,000 K.W. capacity, either for engine, steam-turbine, or water-wheel connection. In general the larger the machine the smaller is the percentage of loss, while the size is limited only by the considerations of mechanical construction, and the possibilities of providing an economical load for the prime movers during light-load periods.

In the evolution of the modern central lighting station, groups of relatively small belted machines occupying large floor space and incurring heavy friction losses have been replaced by a few large generators directly connected to the engine shaft. This change has resulted in superior lighting service, higher efficiency of operation, less complicated switchboards, and diminished costs for repairs and station attendance.

For further descriptions of Typical Forms of Direct-Current Generators, the reader is referred to:

Dynamo-Electric Machinery, S. P. THOMPSON.

Design of Dynamos, S. P. THOMPSON.

The Dynamo, HAWKINS and WALLACE.

Recent Types of Dynamo-Electric Machinery, HOUSTON and KENNELLY.

Dynamo-Electric Machinery, SHELDON and MASON.

Continuous-Current Dynamo, FISHER-HINNER.

Trade Bulletins of the various manufacturing companies, such as the General Electric Co., Westinghouse E. & M. Co., Crocker-Wheeler Co., Brown, Boveri & Co., Siemens-Halske Co., etc.

DIRECT-CURRENT, CONSTANT-CURRENT DYNAMOS FOR ARC LIGHTING.

These machines were formerly adopted almost universally for arc lighting; but arcs lamps are now operated by constant-potential, direct, as well as by alternating, currents, as described in Volume II. Nevertheless this type is employed on many circuits which supply arc lamps only, the latter being arranged in simple series. Since these generators must produce a constant current (usually ten amperes for open arcs and about seven amperes for inclosed arcs) even when the number of lamps on the circuit is changed, they are provided with automatic regulators to keep the current at the proper value. These consist in almost all cases of electromagnetic devices which either shift the commutator brushes, or vary the field-magnetization in order to control the *E.M.F.* generated, and thus maintain a constant current.

In practice, these machines are purposely designed to have considerable armature reaction, magnetic leakage, self-induction, and resistance, which tend to prevent the current from becoming excessive when the resistance of the circuit is reduced by cutting out lamps in series. This helps the regulator to control the current, and gives it time to operate in case the current suddenly increases, as it often does. In fact, an arc dynamo must be capable of being completely short-circuited without injury and without any considerable rise in current. Its design and action are diametrically opposite to those of a constant-potential machine.

The regulator acts to make the current still more uniform; but the effect of armature reaction, etc., is immediate and reliable, preventing great overheating, even if the regulator fails to operate. The action when the current diminishes is to decrease the counter *M.M.F.*, and raise the *E.M.F.*, which tends to keep up the current. But, unfortunately, the field-magnetism does not discharge as rapidly as the counter *M.M.F.* of the armature falls; consequently, if the circuit is suddenly opened, the *E.M.F.* momentarily rises far above its normal value, causing danger to persons, and straining the insulation. This trouble is mitigated by having the armature core highly saturated, so that the flux cannot be increased very much above its ordinary density.

Each particular type of arc dynamo is peculiar, and requires a special description, which would occupy a chapter or more to be

complete. Hence the reader is referred to Thompson's *Dynamo-Electric Machinery*, or other work on the dynamo, where these machines are fully described, only their principal features being given here.

The Brush Dynamo was the first machine to be generally employed for electric lighting. The armature is of the ring form, and consists of a number of separate bobbins wound upon an iron core

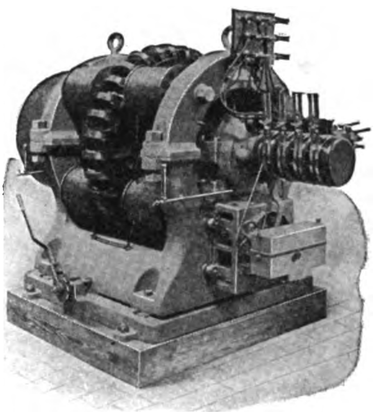


Fig. 144. Brush Arc Generator.

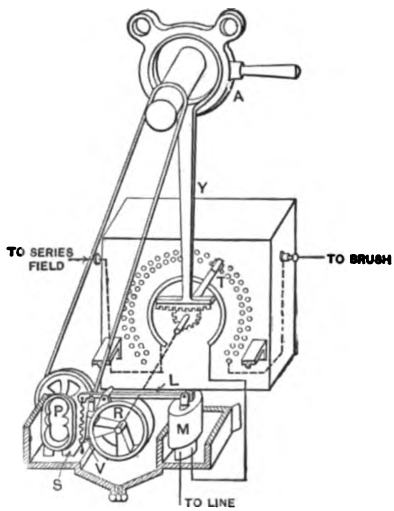


Fig. 145. Regulator of Brush Arc Machine.

which has projections on each side. This armature revolves between the poles of two field-magnets. Usually these are simple horseshoe magnets with two poles, but in the larger machines for 100 lights or more there are four poles on each side (Fig. 144).

Each pair of diametrically opposite armature coils are connected in series, and to an independent pair of commutator sections. By means of the brushes, of which there are ordinarily four or six, the bobbins are connected together, the number of them in series being equal to the number of brushes. For example, in an armature with 12 coils and 6 brushes, there are 3 pairs of bobbins in series. Furthermore, since the commutator sections of coils at right angles overlap each other about 45°, the bobbins are in parallel twice during each revolution, and are out of circuit the rest of the time.

The Brush regulator automatically varies the resistance in parallel with the field winding, and also shifts the brushes so as to maintain

them in a position of minimum sparking. These two operations are performed by the device shown in Fig. 145, which is directly connected to the frame of the generator. This mechanism consists of a rotary oil-pump *P*, driven from the shaft, a balanced cylinder-valve *V*, and a rotary piston *R*, in a short cylinder, which is directly connected to the rheostat arm *T*. The balanced valve is controlled by a lever *L*, which forms the armature of an electromagnet *M*, energized by the full line current. When operating under normal conditions the valve is so placed that the oil flows around the rotary piston without effect. If the current should rise above the normal value, the lever is attracted and lifts the valve, thus causing the oil to act upon the rotary piston in one direction and move the rheostat arm so as to decrease the resistance by which the field-coils are shunted, which reduces the voltage and the current. At the same time a pinion on the shaft of the rheostat arm engages with a rack on the rocker-arm, and shifts the brushes. When the current reaches its proper value the valve is drawn back by a spring, and the oil again flows in and out of the cylinder without effect. Should the current decrease, the spring draws the valve down and admits the oil on the opposite side of the rotary piston and moves the rheostat arm so as to increase the shunted resistance, thus increasing the field-current and voltage. This regulator in conjunction with the armature reaction will bring the current back to its normal value within four seconds after a dead short circuit.

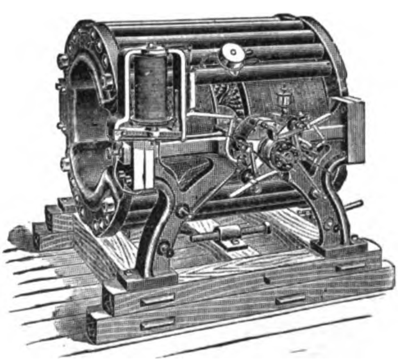


Fig. 146. Thomson-Houston Arc Dynamo.

The Thomson-Houston Arc Dynamo is another very prominent type, having a spherical armature, and the peculiar form of field-magnet shown in Fig. 146. The commutator has only three sections, so that the full voltage exists between adjacent sections, which limits the allowable potential to about 2,500 volts, sufficient for 50 open arcs or 30 inclosed arcs in series. This requires too many machines and circuits, especially for large systems, the modern practice being to put 100 to 200 lamps on a circuit, so that

the manufacture of this type has been discontinued. There are, however, many of these machines in operation.

The Wood Arc Dynamo, shown in Fig. 147, differs essentially from the Brush and Thomson-Houston types in the fact that it has a closed-coil armature, and the commutator is made with a great many sections—usually 100 or more. The armature is a true Gramme ring, the core being formerly composed of annealed iron wire, but it is now built up of laminated punchings of mild sheet steel. The field-magnet is also one of the characteristic forms employed by Gramme. In fact, this machine is directly based upon the original designs and patents of that inventor; but the regulator,

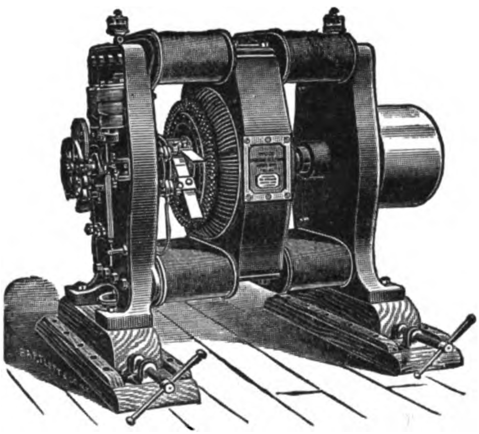


Fig. 147. Wood Arc-Lighting Dynamo.

which is very ingenious and effective, is due to Wood. This consists of an electromagnet controlling a mechanism that shifts the brushes on the commutator as lamps are cut out of circuit, until finally, when the machine is short-circuited, the brushes are almost 90° from their normal position, and the *E.M.F.* becomes very small. The violent sparking which ordinarily occurs when the brushes are displaced from the neutral points is avoided in this dynamo by practically balancing the *M.M.F.* of the field by that of the armature, so that wherever the brushes may be, practically no *E.M.F.* is generated in the coils which are short-circuited by them. This is shown very clearly in the diagrams given by Professor R. B. Owens in a paper on a "Test of a Closed-coil Arc Dynamo," * which contains the results of very careful tests on the

* *Trans. Amer. Inst. Elec. Eng.*, May, 1894.

action and regulation of a 25-light Wood arc dynamo. These machines are made in various sizes up to, and including, 200-light capacity.

ALTERNATING-CURRENT GENERATORS.

The armature windings employed in alternators have already been described in Chapter XVII; and in general they are simpler than those required for direct currents, since they consist merely of a series of coils corresponding in number to the pole-pieces. The field-magnets are usually quite similar to each other in form, as they are almost necessarily multipolar in order to obtain the necessary frequency, which varies from 25 to 133 periods per second.*

When alternators are to be employed for lighting circuits only, single-phase machines are preferable, since they are simpler and do not give rise to the unbalancing of voltages often met with in polyphase work. In modern plants, however, motors as well as lights are supplied with energy, and as the single-phase motor is not the equal of the polyphase motor for general work, it is usually better to install polyphase systems.

So far as general construction and appearances are concerned, single-phase and polyphase alternators are practically identical. About the only important difference is in the arrangement and connections of the armature winding and in the number of collector rings.

Three general types of alternators are in common use:

(*a*) *Machines with revolving armatures and stationary fields.*

(*b*) *Machines with stationary armatures and revolving fields.*

In the latter the armature winding is arranged in slots around the inner periphery of the armature structure. The revolving field is usually provided with radially projecting poles and revolves within the stationary armature. This type has come into extensive use, especially for alternators of large size and high voltage, because the inductors can be better insulated in a stationary armature, and it is more convenient to introduce the field-current through slip-rings than to handle the heavy armature current.

(*c*) *Inductor alternators.* In these machines neither the armature nor field windings revolve. A mass of iron with polar pro-

* Alternating-current principles and methods of transmission and distribution are given in Volume II.

jections is revolved and causes the magnetic flux passing through the armature conductors to vary and thus sets up an alternating electromotive force.

Revolving Armature Alternators are almost universally made in accordance with the general design shown in Fig. 148 in this country, and also to a great extent abroad. The field-magnet resembles the form widely adopted for multipolar, direct-current machines; almost the only difference being the fact that in the latter the space between adjacent pole-pieces is only one-third to one-half of the arc covered by each pole-piece, whereas in alternators the spaces and pole-pieces are usually about equal in extent. Alternators similar to the form shown are manufactured by the General Electric

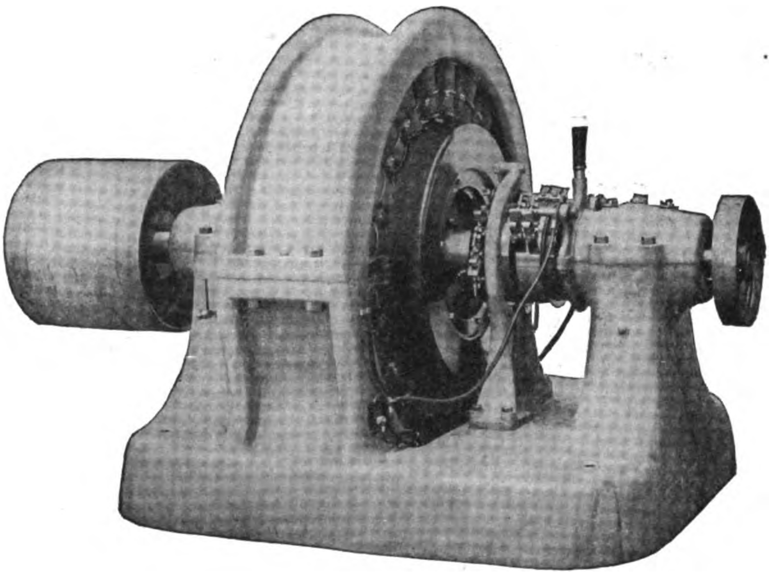


Fig. 148. Revolving Armature Alternator.

and Westinghouse companies, but the tendency is to adopt the revolving field machines in preference, for the reasons stated. The field-magnetizing current is usually obtained from a small auxiliary direct-current dynamo called an "exciter."

These machines are also often made with *composite field-winding,* which is analogous to compound winding for direct-current dynamos, and consists in providing the field-magnets with a few turns of coarse wire in addition to the fine wire winding fed by the exciter. The main current generated by the machine is passed through this

coarse winding, being rectified or converted into a direct current for the purpose by means of the commutator shown on one side of the collecting-rings in Fig. 148. In this way the voltage may be kept constant, or raised with increased load. Instead of passing the main current itself through the extra coils, it is possible to obtain

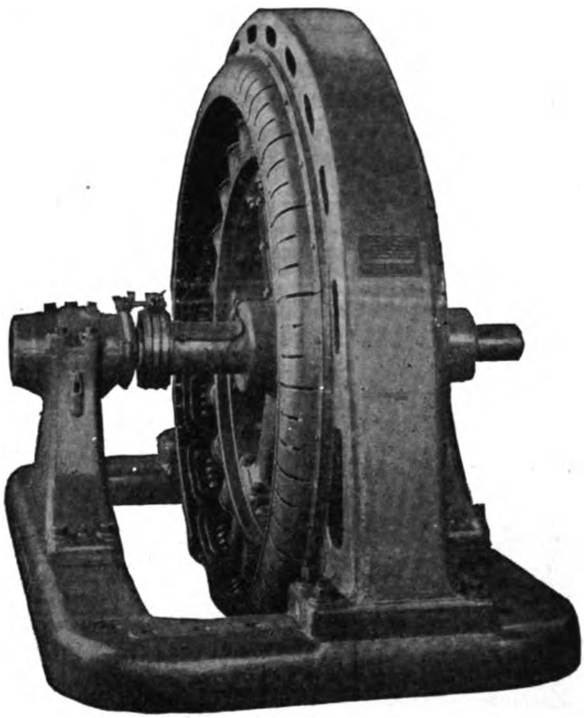


Fig. 149. Revolving-Field Alternator.

the same effect by means of a transformer in which the main current acts inductively upon a secondary circuit, and produces a current proportional to itself, which is rectified and used in a similar way. These constructions are shown and described in Vol. II.

Revolving-Field Alternators.—The special features of design of this type of machine have already been given on page 348, and its use is specially recommended on high-voltage systems, since the insulation of the armature winding can be made heavier and more reliable on a stator than on a rotor. The general appearance of this class of alternator is shown in Fig. 149, which is an illustration of a direct-connected 1,000-K.V.A. two-phase General Electric machine. The collecting-rings on the shaft are for supplying the

field-exciting current, there being no sliding or movable connection between the armature winding and the switchboard leads. A feature common to most designs of this type is the arrangement for shifting the armature structure to one side, so that either it or the field rotor are readily accessible for inspection and repair.

The general construction is shown in Fig. 150. In some designs the magnet cores are built up of laminated sheet steel, bolted to the rotor rim, while in others, especially if the armature core be of

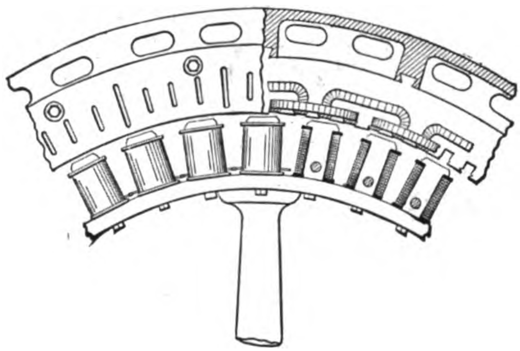


Fig. 150. Construction of Two-Phase Revolving-Field Alternator.

the iron-clad type, the pole cores may be cast as integral parts of the rotor. These machines are built in sizes up to 5,000-K.V.A. capacity, being the type used in the Waterside Station of the New York Edison Company, and in the plants of the Interborough Traction Co. of New York. The compact design of these revolving-field alternators, the fact that the low-voltage part is the revolving member, and that this part may be built exceedingly strong stamps this type as that naturally suited for steam-turbine equipments. An illustration of a revolving-field alternator, in connection with a Curtis Turbine, is shown on page 192.

Inductor Alternators.—The Stanley alternator is one of the most prominent of the inductor type, its general appearance being shown in Fig. 151. The machine is double, having the two stationary armatures, *A* and *A′*, Fig. 152. The two armatures are connected by the iron cross-bars *b*, which carry the magnetic flux, and the armature coils are arranged around the inner periphery of the laminated armature cores in practically the same manner as in the revolving-field machine. The revolving inductor has a set of

laminated polar projections, *p*, at each end, all of one set being of one polarity, and those of the other set of the opposite polarity. The magnetic flux follows the path shown by the dotted line, and as the inductor revolves, the flux passing through the armature coils alternately increases to a maximum and decreases to zero, but does not reverse. The flux is set up by the large stationary coil *C*, which

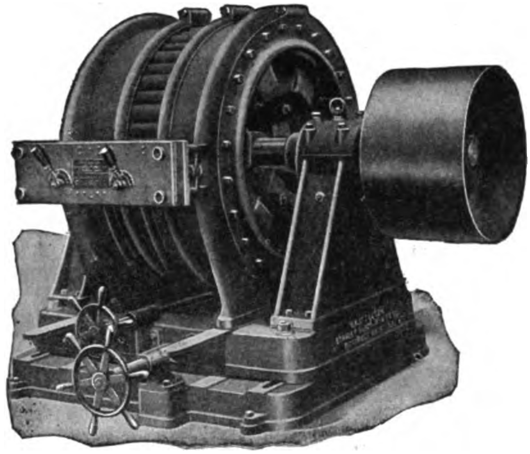


Fig. 151. Stanley Inductor Alternator.

encircles the inductor. The armature coils are arranged to produce two electromotive forces differing in phase by 90°, one set being displaced so that the flux passing through them is at zero, while it is at a maximum through the other set of coils.

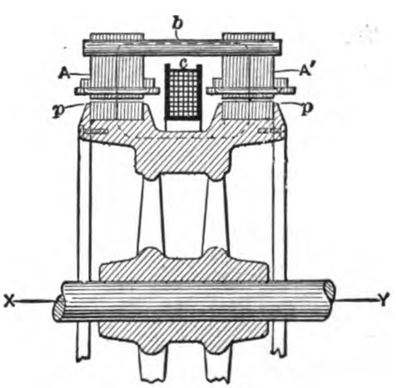


Fig. 152. Construction of Stanley Inductor Alternator.

For additional descriptions of typical alternators, the reader is referred to:

Alternating-Current Machinery, Franklin and Williamson; *Alternating-Current Machines*, Sheldon and Mason; *Polyphase Electric Currents*, S. P. Thompson; *The Dynamo*, Hawkins and Wallace; and *Trade Bulletins* mentioned on page 343.

CHAPTER XIX.

THE PRACTICAL MANAGEMENT OF DYNAMO-ELECTRIC MACHINERY.

THE actual handling of the generators in a central station or isolated plant is an especially important matter in electric lighting. A work by Dr. S. S. Wheeler and the author [1] is devoted to the selecting, installing, operating, and testing of generators and motors, special attention being given to the serious problem of locating and remedying troubles in these machines. The reader is referred to that book for a complete treatment of these subjects, as limitations of space allow only the principal points to be given in the present chapter.

The Selection of a Generator.—One of the first questions that the electrical engineer is called upon to decide is the selection of a machine for a certain plant. It depends largely upon circumstances in each particular instance, but there are certain general principles which apply to almost all cases.

Construction. — This should be of the most solid character, and first-class in every respect, including materials and workmanship.

Finish. — A good finish is desirable, — first, because it indicates good construction; second, it stimulates the interest and pride of the attendant; and third, it shows the least dirt or neglect.

Simplicity. — The machine and all its parts should be as simple as possible, and any peculiar or complicated feature should be avoided. These are sometimes successful, but should be well tried and proved before being accepted.

Attention. — The amount of attention required by the machine should be small. The screws, connections, and other small parts should be arranged so that they are not likely to become loose, and the delicate parts should not be exposed or liable to injury.

[1] *The Practical Management of Dynamos and Motors*, by F. B. Crocker and S. S. Wheeler, D. Van Nostrand Co., New York.

Handling. — The machine should be provided with an eye-bolt or other means by which it can be easily lifted or moved without injury. It ought to be possible to take out the armature conveniently by removing one of the bearings or the top of the field-magnet.

Interchangeability. — Machines should be made with interchangeable parts, so that a new piece which will fit perfectly can be readily obtained; for this reason regular and established types are preferable to special or unsettled forms.

Regulation. — Some form of regulator should be provided by which the *E.M.F.*, or current, can be reliably and accurately governed.

Capacity. — This should be ample in all cases. It is a very common mistake to underestimate the work required of a given machine; and, even if it has sufficient power at first, the demands upon it are apt to increase, and finally overload it. No one is ever likely to regret choosing a dynamo having a reasonable margin of capacity, since these machines only consume power in proportion to the work they are doing. For example, a 25 kilowatt generator would probably run with a 20 kilowatt load more economically and satisfactorily than a 20 kilowatt machine with the same load.

Form. — The dynamo should be symmetrical, well-proportioned, compact and solid in form. If it is either very tall or very flat, it is usually inconvenient and clumsy. No part should project excessively, or be awkwardly formed or arranged. The large and heavy portions should be placed as low as possible, to give great stability. For the same reason the shaft should not be high above the base, nor should it be so low that there is not ample room for the pully or other attachment. A horizontal belt, for example, will sag and strike the floor if the pulley is very low.

Weight. — The common idea that it is desirable to have a very light dynamo is a mistake when it is for stationary use. There is no advantage in a light machine except portability; and it has the disadvantages of being less strong, less durable, and less steady in running. A sufficient weight to make it thoroughly substantial is obviously a great benefit.

Cost. — It is also a mistake to select a cheap machine, since both the materials and workmanship required in a high-quality

dynamo or motor cost more than in almost any other machine of the same size and weight. It is an undeniable fact that there has been considerable trouble with electrical machinery owing to inferior construction.

In addition to these general considerations, the armature, field-magnets, and other parts of a dynamo, should be made in accordance with the facts given in Chapter XVII.

These suggestions as to selecting a dynamo or motor may be followed when it is possible to make merely a general examination of the machine, or even in cases where it is only practicable to obtain a drawing or description of it. But to make a complete investigation, it is necessary to carry out a thorough test, and measure exactly its various constants.

A satisfactory test cannot usually be made, however, until after the machine is set up in place; and, moreover, it is not generally necessary if it is obtained from a reputable source.

The Number and Size of Units. — The question of selecting the best size and number of dynamos in an electrical plant is not nearly so serious as the corresponding problem in connection with steam-engines; because, as already stated, the efficiency of a dynamo is higher, and is not reduced to anything like the extent at light loads. A dynamo is usually not very much less efficient at one-quarter load than at full load, while a steam-engine is only about one-third as efficient.* There is rarely any necessity, therefore, for running a dynamo at a low efficiency; since it would not require much engineering skill to design a plant in which no dynamo was obliged to operate at less than one-quarter load. It is also a fact that small dynamos of only 50 kilowatts capacity can be made to give an efficiency of 90 per cent, and are nearly as good in this respect as larger machines; so that the electrical generating plant can be subdivided, if desired, without detriment, except the multiplicity of units. It is, therefore, very evident that the size and number of dynamos should be suited to the requirements of the engines, since the difficulty lies with the latter.

A point which is often misunderstood is the fact that the efficiency of a dynamo at full load is not so important as at *average* load. Assume, for example, a dynamo having an effi-

* See page 199.

ciency shown by the curve *OBA* in Fig. 153, and another machine whose efficiency is represented by the curve *OCD*. It would be in accordance with common practice to compare these two dynamos at full load, at which the efficiency of the first is only 85 per cent, while the other gives 90 per cent. But, as a matter of fact, the first machine (*OBA*) is far better than the second; since its *average* efficiency is much higher, and is nearly 90 per cent between one-half and three-quarters of its full power, which would be the range of its ordinary working-load. It should always be remembered that full load is a *limit* which should be

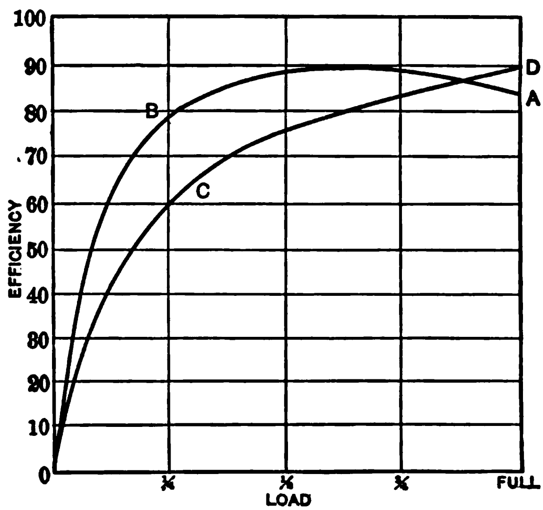


Fig. 153. Efficiency of Dynamos.

but occasionally reached, and then only for short periods of time. Cases might arise in which dynamos would be run steadily at full load, but they would be rare.

Setting up a Dynamo. — The location and foundations for dynamos have already been discussed in Chapter VI., and it will be assumed that they are ready when the machine arrives.

In unpacking and putting the machines together, the greatest possible care should be used in *avoiding the least injury to any part*, in *scrupulously cleaning each part*, and in *putting the parts together in exactly the right way*. This care is particularly important with regard to the shaft, bearings, magnetic joints, and electrical connections, from which every particle of grit, dust, chips

of metal, etc., should be removed. It is very desirable to have machinery assembled by a person thoroughly familiar with its construction; and in the absence of such a person no one should attempt it without at least a drawing or photograph of the apparatus as a guide. An exception may be made to this rule if the machine is very simple, and the way to put it together is perfectly obvious; but in no event should the installation or management of machinery be left to guess-work. The armature must be handled with the greatest possible care, in order to avoid injury to the wires and their insulation, as well as to the commutator and shaft. It should be supported by the shaft, to avoid any strain on the armature-body or commutator. If it is necessary to lay the armature on the ground, interpose a pad of cloth; but it is much better to rest the shaft on two wooden horses or other supports. The proper speed for a dynamo should always be obtained from its manufacturers, and this speed should not be departed from without their approval. Belting, direct coupling, and other means of connecting dynamos with engines, have already been treated in Chapters XV. and XVI.

The direction of rotation of the various machines is sometimes a matter of doubt or trouble. Almost any dynamo is intended to be run in a certain direction; that is, it is called right-handed or left-handed according to whether the armature does or does not revolve like the hands of a clock when looked at from the pulley end. Dynamos are usually designed to be right-handed, but the manufacturer will make them left-handed if specially ordered. This may be required because the pulley to which the machine is to be connected happens to revolve left-handed; or it may be necessary in order to bring the loose side of the belt on top, or to permit the machine to occupy a certain position where space is limited. To reverse the direction of rotation of an ordinary shunt, series, or compound-wound, direct-current, two-pole dynamo, the brushes may simply be reversed, without changing any connection. This changes the point of contact of the brush-tips 180°. If the machine is multipolar, a similar change must be made, amounting to 90° in a four-pole, 45° in an eight-pole, machine, etc. The direction of the current and the polarity of the field-magnets remain the same as before; all that is changed is the direction of rotation and the position of the brushes. This

applies to any machine except arc dynamos and one or two other peculiar machines, which require to be run in a certain direction to suit the regulating apparatus. A separately excited alternating-current dynamo can be reversed in direction of rotation without changing any connection. A self-exciting or compound-wound alternator requires the brushes that supply the direct current to the field to be reversed upon the commutator, and their tips moved through an angle, as above, if the rotation be reversed.

If the direction of the current generated by a dynamo is opposite to that desired, the two wires leading out of it should exchange places in the terminals; or, if this is not desired, the residual magnetism may be reversed by a current from a battery or other source.

DIRECTIONS FOR STARTING DYNAMOS.

General. — The machine should be clean throughout, especially the commutator, brushes, electrical connections, etc. Any metal-dust must be carefully removed, as it is very likely to make a ground or short circuit.

Examine the entire machine carefully, and see that there are no screws or other parts that are loose or out of place. See that the oil-cups have a sufficient supply of oil, and that the passages for the oil are clear, and the feed is at the proper rate. In the case of self-oiling bearings, the rings or other means for carrying the oil should work freely. See that the belt is in place, and has the proper tension. If it is the first time the machine is started, it should be turned a few times by hand, or very slowly, in order to make sure that the shaft revolves easily, and the belt runs in the centers of the pulleys.

The brushes are carefully examined, and adjusted to make good contact with the commutator and at the proper point, the switches connecting the machine to the circuit being left open. The machine should then be started with care, and brought up to full speed, gradually if possible; and in any case the person who starts a dynamo should be ready to stop it instantly if the least thing seems to be wrong, and should then be sure to find out and correct the trouble before starting again. (See "Locating and Remedying Troubles.")

Starting a Dynamo. — A dynamo is usually brought up to speed either by starting up a steam-engine, or by connecting the dynamo

to a source of power already in motion. The former should, of course, only be attempted by a person competent to manage steam-engines, and familiar with the particular type in question. The mere mechanical connecting of a dynamo to a source of power is usually not very difficult; nevertheless, it should be done carefully and intelligently, even if it only requires throwing in a friction-clutch or shifting a belt from a loose pulley. To put a belt on a pulley in motion is difficult and dangerous, particularly if the belt is large or the speed is high, and should not be tried except by a man who knows just how to do it. Even if a stick is used for this purpose, it is apt to be caught and thrown around by the machinery unless it is used in exactly the right way.

A single dynamo working alone on a circuit without danger of short-circuiting another dynamo or storage battery is easily started and connected to the circuit; but it usually happens in electric lighting, where the number of lamps required to be fed varies so greatly, that one dynamo may be sufficient for certain hours, but two, three, or more machines may be required at other times.

In such cases several dynamos may be connected together, either in parallel (multiple arc) or in series.

Dynamos in Parallel. — In this case the + terminals are connected together or to the same line, and the − terminals are connected together or to the other line. The currents (i.e., amperes) of the machines are thereby added, but the *E.M.F.* (volts) is not increased. The chief condition for the running of dynamos in parallel is that their voltages shall be equal, but their current capacities may be different. Parallel working is therefore suited to constant-potential circuits. A dynamo to be connected in parallel with others, or with a storage battery, must first be brought up to its proper speed, *E.M.F.*, and other working conditions; otherwise it might short-circuit the system, and burn out its armature. In fact, a dynamo should not be connected to a circuit in parallel with others until its voltage has been tested, and found to be equal to, or slightly (not over 1 or 2 per cent) greater, than that of the circuit. If the *E.M.F.* of the dynamo is less than that of the circuit, the current will flow back into the dynamo, and cause it to be run as a motor. The direction of rotation is the same, however, in a shunt-wound dynamo; and no great harm results from a slight difference of potential. In fact, such

machines are self-adjusting, since if one tends to run too fast it has to do more work, and *vice versa;* but compound-wound machines require more careful handling.

The test for equal voltages may be made by first measuring the *E.M.F.* of the circuit, and then of the machine, by one voltmeter; or voltmeters connected to each may be compared. Another method is to connect the dynamo to the circuit through a high resistance and a galvanometer; and when the latter indicates no current, it shows that the voltage of the dynamo is equal to that of the circuit. A rougher and simpler way to do this is to raise the potential of the dynamo until its "pilot-lamp," or other lamp fed by it, is fully as bright as the lamps on the circuit, and then connect the dynamo to the circuit. Of course the lamps compared should be intended for the same voltage and in normal condition.

When the dynamo is first connected in this way, it should only supply a small amount of current to the circuit (as indicated by its ammeter), and its voltage should then be gradually raised until it generates its proper share of the total current; otherwise it will cause a sudden jump in the brightness of the lamps on the circuit.

Series-wound Dynamos in Parallel not Used. — If the machine is series-wound, the back current just described would cause a reversal of field-magnetism and a serious short-circuit. In fact, series dynamos in parallel are in very unstable equilibrium; because if either tends to generate too little current, that fact weakens its own field, which is in series, and thus still farther reduces its current, and finally reverses the machine. One way in which this difficulty might be overcome, is by causing each to excite the other's field-magnet, so that if one generates too much current, it strengthens the field of the other, and thus counteracts its own excess of power.

Another plan is to excite both field-magnets by one of the dynamos; but the best method is to connect together the two brushes which convey the current from the armatures to the fields in the two machines, by what is called an "equalizer" (Fig. 154), or "Gramme wire." By this means the electrical pressure at the terminals of the two armatures is made the same, and the currents in the two fields are also made equal. Series machines

are not often run in parallel, but the principles just explained help the understanding of the next case, which is extremely important.

*Compound Dynamos in Parallel.**—Since the field-magnets of these machines are wound with series as well as shunt coils, the

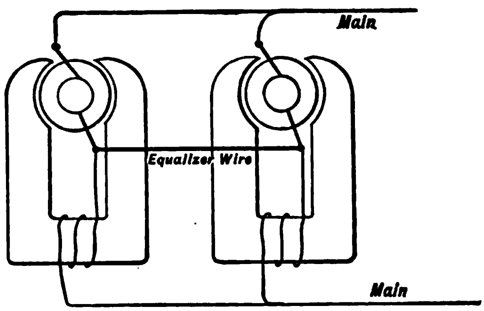


Fig. 154. Series-Wound Dynamos in Parallel.

coupling of them is a combination of the cases of the shunt and the series-wound machines just described.

Assume that one machine is already running, that switches *D'*, *E'*, and *F'* (Fig. 155) are closed, and that the armature of No. 1 is

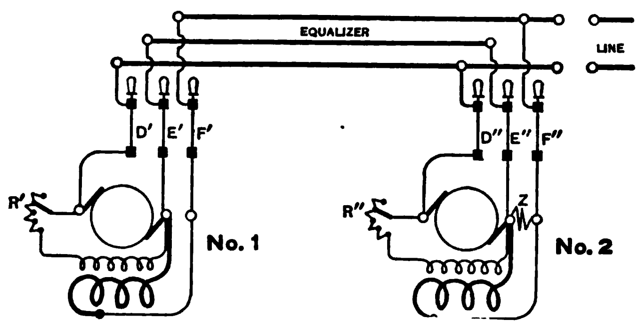


Fig. 155. Compound-Wound Dynamos in Parallel.

generating its full current, and feeding the lamps on the main circuit, the shunt and series field-coils of the machine carrying their proper current. Now, to throw on the other dynamo, its armature (No. 2) is brought up to normal speed, switches *E''* and *F''* are closed, which excites its series-coil with part of the main current from No. 1. It is then necessary to compare carefully the voltage of generator No. 2 with that of the circuit by means of the same or

* In discussion of various methods of connecting generators in parallel, see Chap. III., Vol. II.

separate voltmeters, regulating it with the rheostat R'' until the former is about one per cent higher.

The main switch D' is then closed and the machine should generate a small amount of current. Finally it is made to produce its proper share, as shown by its ammeter, by still further raising its E.M.F. (internal) by means of its field rheostat R''. With compound dynamos considerable care is required to avoid a back current through the series coil tending to demagnetize the field, as already stated.

In disconnecting a machine, the same steps are taken in exactly the reverse order. Any number of compound-wound dynamos may be run in parallel in this way; and even those of different size or current capacity may be connected, provided their voltages agree, and provided also that the resistances of their series field-coils are inversely proportional to the current capacities of the several machines. Dynamos which are compound-wound to maintain a constant potential at their terminals work well after their voltages are once made to agree, even with a variable load. But machines which are "over-compounded" to generate a higher potential at greater loads must give exactly the same percentage of increase at full load, and must agree at all intermediate points, otherwise the dynamo which tends to produce a higher voltage will generate more than its share of the current. This may be overcome if the resistance of the series-coil of the machine which tends to take too large a share of the load is slightly increased, by simply interposing a few extra feet of conductor of the same current capacity as the series-coil, and between it and the main conductor or 'bus bar. The shunt which is almost always used to adjust the effect of the series-coils in compound dynamos (shown at Z in machine No. 2, Fig. 155) operates properly in the case of machines working *singly*, but is worthless for machines in parallel, since it affects all the dynamos alike, and simply reduces their voltage equally. Hence a shunt should be used when this latter result is desired; but the action of individual generators should be adjusted by varying the resistance of the series-coils themselves, as described above.

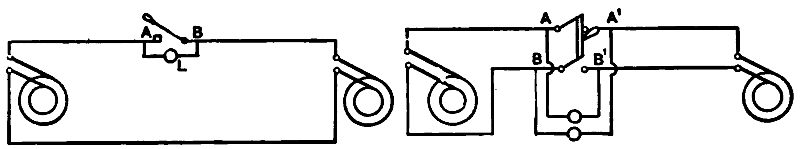
Another difficulty which arises with over-compounded dynamos in parallel, is the fact that when, for example, one machine out of four is working alone at one-quarter of the total load, it

will be fully loaded, and will generate the maximum voltage, while the loss of potential on the conductors is only one-quarter of the maximum. The pressure at the lamps will therefore be too high by an amount equal to three-quarters of the full drop. This very objectionable excess of voltage at the lamps may be avoided by merely leaving the equalizer (switch *E*, Fig. 155) connected to all the dynamos, so that the currents in the series-coils will be proportional to the *total* load, and not to the load on each machine. In the case of high-potential dynamos, it would be dangerous to have them connected to the circuit when they were stopped for cleaning and repairs, consequently a resistance exactly equivalent to the series-coil should be substituted between the equalizer and the 'bus bar, whenever a machine is disconnected from the circuit. This matter has been quite fully discussed by Professor E. P. Roberts and the author in the *Electrical World*, Oct. 13, Dec. 1, and Dec. 8, 1894.

Alternators in Parallel.—To run two alternators in parallel, several conditions have to be fulfilled: The incoming machine—as in the case of direct-current generators—must be brought up to nearly the same voltage as the first one; it must operate at exactly the same frequency; and, at the moment of switching in parallel, it must be in phase with the first machine. This correspondence of frequency and phase is called synchronism.

It is impossible with mechanical speed-measuring instruments to determine the speed as accurately as is necessary for this purpose. There is, however, a very simple means of electrically determining small differences in speed or frequency. In Fig. 156, let *M* and *N* represent two single-phase alternators, which can be connected by means of the single-pole switch *AB*. Across the terminals of the switch is connected an incandescent lamp *L*, capable of standing twice the voltage of either machine. When *AB* is open, the circuit between the machines is completed through *L*. The two machines may be connected in parallel as follows: Assuming machine *M* already in operation, bring up machine *N* to approximately the proper speed, and watch lamp *L*. If machine *N* is running a very little slower or faster than machine *M*, the lamp *L* will glow for one moment and be dark the next. At the instant when the voltages are equal in pressure and phase, *L* will remain dark; but when the two are displaced by half a period, the lamp

will glow at its maximum brilliancy. Since the flickering of the lamp is dependent upon the difference in frequency, the machines, so long as this flickering exists, should not be thrown in parallel. The prime mover of the incoming machine must be brought to the proper speed; and the nearer machine N approaches synchronism, the slower the flickering. When it is very slow, we can use the moment the lamp is dark to throw the machines in parallel by closing the switch across AB. The machines are then in phase, and tend to remain so, since if one slows down the other will drive it as a motor. It is better to close the switch when the machines are approaching synchronism than when they are receding from it, that is, at the instant the lamp becomes dark.



Figs. 156 and 157. Alternators in Parallel.

This method of synchronizing is open to the following objections:

(*a*) The lamps may be dark with considerable difference in voltage. For instance, a 110-volt lamp is dark with a pressure of 20 to 25 volts.

(*b*) The lamp may be dark owing to a broken filament.

It may thus happen, with this arrangement, that the machines are placed in parallel while there is a considerable difference of voltage or phase existing, and an excessive rush of current will result.

A method not open to the above objections is shown in Fig. 157. The alternators to be thrown in parallel are each connected to the bus-bars by means of double-pole switches. Two incandescent lamps, of the machine voltage, are cross-connected as shown. If the machines are in phase and the voltages generated are equal in value, the difference of potential between A and a given point is the same as that between A' and the same point; likewise B and B' have the same relative potential values. Hence a lamp connected between A and B' would burn with the same brilliancy as if connected directly across AB, which is also true of the other

lamp. If, however, the machines happen to be directly opposite in phase, but generating voltage of the same value, A and B' are of the same potential, B and A' being also of equal value; hence lamps cross-connected as in Fig. 157 would be dark. At other phase differences the lamps will glow, but not as brightly as when there is no difference in phase. Hence, with this arrangement, the machines should be thrown in parallel when the lamps are on the verge of maximum brightness, a condition readily determined, but not possible with the first method.

The connections as shown in Figs. 156 and 157 are not directly applicable to high-tension working, but require the introduction of transformers as shown in Fig. 158, which is a modification

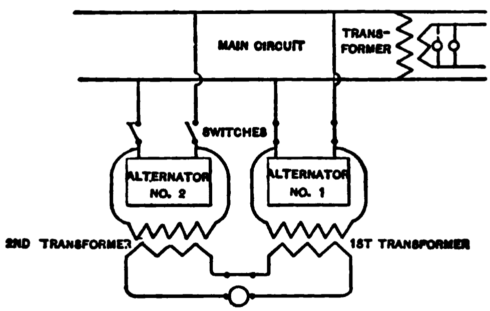


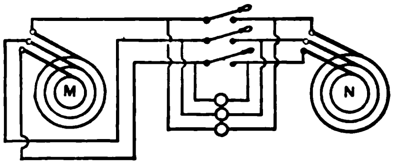
Fig. 158. High-tension Alternators in Parallel.

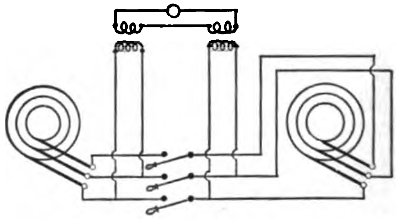
of Fig. 157. The secondaries (of, say, 50 volts each) should be connected in series with each other and to one 100-volt lamp. When the two machines are opposed in phase, the lamp is dim. If the lamp flickers badly, the phase is not right; but if the lamp is steady at full brightness, the machines are in phase, and they may be connected without disturbing the circuit, by closing the main switch.

If alternators are rigidly connected to each other or to the engine, so that they necessarily run exactly together, there is no need of bringing them into step each time, but they should be adjusted to the same phase in the first place.

The connections of the synchronizing lamps of a three-phase system are similar to those for a single-phase system. For instance, the method employed in Fig. 156 may be extended, and lamps connected as in Fig. 159. If the three lamps simultaneously become dark or bright, the connections are correct, and the three switches

may be closed at an instant of darkness. It may happen, however, that the lamps do not become bright or dark simultaneously, but successively. This indicates that the order of connection of the leads of one machine does not correspond with that of the other. In this case, transpose the leads of one machine until the proper or simultaneous action of the lamps is obtained. After the machines have been properly connected, it is sufficient to synchronize





Figs. 159 and 160. Alternators in Parallel.

with one of the lamps. Similarly, with high-tension systems, only a single-phase transformer is required, connected as shown in Fig. 160.

Generators in Series.—This arrangement is much less common than parallel working, being only applied to series-wound dynamos on arc circuits and to "boosters" (see page 39). The conditions are exactly opposite to those of dynamos in parallel.

To connect machines in series, the positive terminal of one must be connected to the negative terminal of the next; and each must have a current capacity equal to the maximum current on the circuit, but they may differ to any extent in *E.M.F.* The voltages of machines in series are added together; and therefore danger to persons, insulation, etc., is increased in proportion.

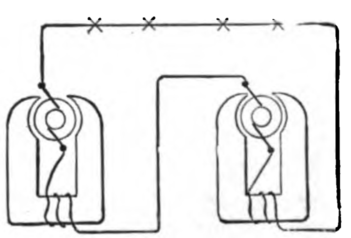


Fig. 161. Series-Wound Dynamos in Series.

Series-wound dynamos in series are connected in the simple way represented in Fig. 161, but usually machines connected in series are for arc lighting; for example, when two dynamos, each of 40 lights capacity, are run on one circuit of 80 lamps, in which

case the dynamos usually have some form of regulator. These regulators do not ordinarily work well together, because they "seesaw" with each other. This difficulty may be overcome, either by connecting the regulators so that they must work together, or by setting one regulator to give full *E.M.F.*, and allowing the other to control the current. This latter plan can only be followed when the variation in load does not exceed the capacity of the regulating-machine.

Shunt or compound dynamos in series run well provided the shunt field-coils are connected together to form one shunt across both machines. If the machine is compound, the series-coils must be connected in series in the main circuit. Another plan is to connect each shunt-field so that it is fed only by the armature of the other machine; or both the shunt-coils may be connected so as to be fed by one armature, the series-coils being in the main circuit, as before.

Alternators in Series.—The synchronizing tendency which makes it possible under certain circumstances to run alternators in parallel, causes them to get out of step and become opposed to each other when it is attempted to put them in series. It is therefore impracticable to put them in series unless their shafts are rigidly connected together, so that they must run exactly in phase, and add their waves of current, instead of counteracting each other. This is a case that rarely arises in practice.

Dynamos on the Three-wire System (Direct Current).—In the ordinary three-wire system for incandescent lighting, no particular precautions are required in starting or connecting dynamos. As a matter of fact, the two sides of the system are almost independent of each other, and form practically separate circuits, for which the middle or neutral wire acts as a common conductor. There is, however, a tendency for the dynamos to be reversed in starting up, shutting down, or in case of a serious short circuit. This may be avoided by exciting the field-coils of all the dynamos from one side of the system, or by means of a separate dynamo.

DIRECTIONS FOR RUNNING DYNAMOS.

When a dynamo has been properly started, it usually requires very little attention while running; and it often runs well all day without any care whatever.

In the case of a machine which has not been run before, or has been changed in any way, it is wise to watch it closely at first. It is also well to give the bearings of a new machine plenty of oil in the beginning, but not enough to get on the armature, commutator, or any part that would be injured by it; and the belt ought to be rather slack until the bearings have gotten into easy working condition. If possible, a new machine should be run without load, or with a light one, for several hours; and it is always wrong to start a new machine with its full load, or even a large fraction of it. This is true even if the machine has been fully tested by its manufacturer and is in perfect condition, because there may be some fault in setting it up which would cause trouble. All machinery requires some adjustment and care for a certain time to get it into smooth working order.

The person in charge should always be ready and sure to detect the beginning of any trouble, such as sparking, the heating of any part of the machine, noise, abnormally high or low speed, etc., before any injury is caused, and to overcome it by following the directions given later.

Special care should be observed by any one who runs a dynamo to avoid *overloading* it, because this is the cause of most of the troubles which occur.

Personal Safety. — Never allow the body to form part of a circuit. While handling a conductor, a second contact may be made accidentally through the feet, hands, knees, or other part of body, in some peculiar and unexpected manner. For example, men have been killed because they touched a "live" wire while standing or sitting upon a conducting body.

Rubber gloves or rubber shoes, or both, should be used in handling circuits of over 500 volts. The safest plan is not to touch any conductor while the current is on; and it should be remembered that the current may be present when not expected, due to an accidental contact with some other wire or to a change of connections. Tools with insulated handles, or a dry stick of wood, should be used instead of the bare hand.

The rule to use *only one hand* when handling dangerous electrical conductors or apparatus is a very good one; because it avoids the chance, which is very great, of making contacts with both hands, and getting the full current directly through the body.

The above precautions are often totally disregarded, particularly by those who have become careless by familiarity with dangerous currents. The result of this has been that *almost all the persons accidentally killed by electricity have been experienced electricians or electrical workmen.*

DIRECTIONS FOR STOPPING DYNAMOS.

Dynamos may be stopped by following substantially the same directions as those given for starting them, but in the reverse order.

A generator operating *alone* on a circuit can be slowed down and stopped without touching the switches, brushes, etc., in which case the current gradually decreases to zero; and then the connections can be opened or changed without sparking or other difficulty.

When, however, a dynamo is working in parallel with others, or with a storage battery, it must not be stopped or reduced in speed until it is entirely disconnected from the circuit, otherwise it will act as a short-circuit. Furthermore, the current generated by it should be reduced nearly to zero before its switch is opened. This is usually accomplished by adjusting the field-regulators of either direct- or alternating-current machines.

A constant-current dynamo may be cut into or out of circuit in series with others, and can be slowed down or stopped, or its armature or field coils may be short-circuited to prevent the action of the machine, without disconnecting it from the circuit. It is absolutely necessary, however, to preserve the *continuity* of the circuit, and not attempt to open it at any point, as it would produce a dangerous arc. Hence a path must be provided by closing the main circuit around or past the dynamo before disconnecting it. The same rule applies to any lamp, motor, or other device on a constant-current circuit.

It will be observed that in all cases the generator should not be disconnected until its current is reduced to an insignificant value; and never, except in an emergency, should a circuit be opened at full or even half load, for the reason that the flash at the contact points, discharge of magnetism, and mechanical shock which result are decidedly objectionable.

Immediately after a machine is stopped, it should be thoroughly

cleaned, and put in condition for the next run; since this can be done much more easily while it is still warm. When not in use, machines should be protected from dirt and moisture by covers of rubber, oiled canvas, or enamel cloth.

DISEASES OF DYNAMOS.

In the work by Dr. S. S. Wheeler and the author, to which reference was made in the beginning of this chapter, the subject of "Locating and Remedying Troubles in Dynamos and Motors" is treated in detail, about seventy pages being devoted to it. It is impossible to devote much space to this matter in the present volume; but its importance is such that the list of possible troubles is herein given, and whenever feasible the symptoms and remedies have also been included.

It is evident that the subject is somewhat complicated, and difficult to handle in a general way, since so much depends upon the particular conditions in any given case. Nevertheless, it is quite remarkable how much can be covered by a systematic statement of the matter.

It frequently happens that a trifling oversight, such as allowing a wire to slip out of a binding-post, will cause as much annoyance and delay in the use of electrical machinery as the most serious accident. Other troubles, equally simple, but not as easily detected, are of frequent occurrence. In such cases a very slight knowledge on the part of the man who runs a dynamo will enable him to overcome the difficulty immediately, and save much time, trouble, and expense.

It should be remembered by those in charge that it is usually better to STOP the machine when any trouble manifests itself, even though the difficulty does not seem to be very serious, because it is very likely to develop into something worse. There are, of course, many cases, particularly in electric lighting, when it is almost impossible to shut down; but even then spare machines should always be ready to be quickly substituted for the defective one. The continued use of faulty apparatus is too common a practice, and is often inexcusable. Neglect and carelessness with any machine are usually and deservedly followed by accidents of some sort.

The general plan here followed is to divide all troubles which

may occur to dynamos into eight classes, the headings of which are the most important and obvious bad effects produced in these machines; viz.: —

1. *Sparking at the Commutator.*
2. *Heating of Commutator and Brushes.*
3. *Heating of Armature.*
4. *Heating of Field-magnets.*
5. *Heating of Bearings.*
6. *Noise.*
7. *Speed too Low.*
8. *Failure to Generate.*

Any one of these general effects is very evident, even to the casual observer, and each one of them is perfectly distinguishable from any of the others, thus eliminating about seven-eighths of the possible cases. The next step is to find out which particular one of eight or ten causes in this class is responsible for the trouble. This requires more careful examination; but, nevertheless, it can be done with comparative ease in most cases.

SPARKING AT THE COMMUTATOR.

This is one of the most common troubles; the objection to it being that it wears, or may even destroy, the commutator and brushes, and produces heat, which may injure the armature or bearings. Any machine having a commutator is liable to it, including practically all direct-current, and some alternating-current, machines. The latter have continuous collecting-rings which are not likely to spark, but self-exciting or compound-wound alternators require a supplementary continuous-current commutator that may spark. This trouble can be prevented in most cases, however, by proper construction and care. The following causes of sparking apply to nearly all machines, and they cover closed-coil dynamos especially.

The very peculiar cases which may arise in the particular types of open-coil armatures (Brush and Thomson-Houston) can only be reached by special directions for each. A certain amount of sparking occurs normally in most constant-current dynamos for series arc lighting, where it is not very objectionable, since they are designed to stand it, and the current is small.

The principles and conditions relating to sparking are given in Chapter XVII. See also article on "Sparking of Closed-coil Dynamos," by G. F. Hanchett, *Electrical World*, Dec. 29, 1894.

1. **Cause.** — *Armature carrying too much current*, due to (*a*) overload (for example, too many lamps fed by the dynamo); (*b*) short circuit on the conductors; (*c*) excessive voltage on a constant-potential circuit, or excessive amperes on a constant-current circuit.

2. *Brushes not set at the neutral point.*

3. *Commutator rough, eccentric, or has one or more "high bars"* projecting beyond the others, or one or more *flat bars*, commonly called "flats," or *projecting mica*, any one of which causes brush to vibrate, or to be actually thrown out of contact with commutator.

Remedy. — Smooth the commutator with a fine file or fine sandpaper, the latter being applied by a block of wood which exactly fits the commutator (be careful to remove any sand or copper dust remaining afterward; *and never use emery*). If commutator is very rough or eccentric, the armature should be taken out and put in a lathe, and the commutator turned off. Large machines sometimes have a slide-rest attachment, so that the commutator can be turned off without removing the armature from its bearings.

In turning a commutator in the lathe, a diamond-pointed tool should be used, having a very sharp and smooth edge, and only an exceedingly fine cut should be taken off each time. The surface is then finished by applying a "dead smooth" file while the commutator revolves rapidly in the lathe. Any particles of copper should then be carefully removed from between the bars. Sometimes a *very little* vaseline, or a drop of oil, may be applied to a commutator which is rough. Too much oil is very bad, and causes the following trouble: —

4. *Brushes make poor contact with commutator;* that is, they touch only at one corner, or only in front or behind, or there is dirt on surface of contact. Sometimes, owing to the presence of too much oil, or from other cause, the brushes and commutator become very dirty. Insufficient pressure also gives poor contact.

5. *Short-circuited or reversed coils in armature.* — The former become heated even after a few minutes' run.

6. *Broken circuit in armature.*

7. "*Grounds*" *in armature* (i.e., accidental contact between the conductors and the core). See paper on "Location of Grounds in Armatures, Fields," etc., read by C. E. Gifford before Amer. Inst. Elec. Eng., June 25, 1895.

8. **Cause.** — *Weak field-magnetism.*

Symptom. — Voltage low, pole-pieces not strongly magnetic, non-sparking point of brushes shifted from normal position.

Remedy. — In a shunt-wound machine this trouble is probably due to a poor contact, or other excessive resistance in the field-circuit.

9. *Unequal distribution of magnetism.* — One pole-tip is much weaker than the other (of the same pole-piece), due to too great armature reaction compared with *M.M.F.* of field-magnet.

10. *Very high resistance brush.* — A carbon brush may have too high resistance to make sufficiently good contact.

11. *Vibration of machine,* usually due to imperfect balance of armature or pulley or to a faulty belt.

12. *Chatter of brushes.* — This occurs with carbon brushes, particularly when they are radial, and if commutator is sticky.

Remedy. — A very little oil will usually stop it.

13. *Pulsations of current.* — Variations in, or surgings of, the current, due to action of engine governor or other cause.

14. "*Flying*" *break, or short circuit, in armature conductors,* which only exists when armature is running, and is usually due to centrifugal force.

HEATING IN DYNAMO.

The degree of heat that is injurious or objectionable in a dynamo or motor is easily determined by applying the hand to the various parts. If the heat is bearable, it is entirely harmless. But if the heat is unbearable for more than a few seconds, the safe limit of temperature has been passed, except in the case of commutators in which solder is not used. In testing with the hand, allowance should always be made for the fact that bare metal seems much hotter than cotton, etc. If the heat has become so great as to produce an odor or smoke, the safe limit has been far exceeded, and the current should be shut off, and the machine stopped immediately, as this indicates serious trouble.

The effect of heat on the insulation of wires, and the temperature at which it is injured, have been investigated by Reeve.* Neither water nor ice should ever be used to cool electrical machinery, except possibly the bearings of large machines, where it can be applied without danger of wetting the other parts.

Determining heat by feeling will answer in ordinary cases; but the sensitiveness of the hand differs, and it makes a great difference whether the surface is a good or bad conductor of heat. The back of the hand is more sensitive and less variable than the palm for this test. For more accurate results a thermometer should be applied, and covered with a small pad of cloth or waste. The surface temperature of any portion of the machine should not rise more than 40° C. or 72° F. above that of the surrounding air, except commutators and collector rings, for which 55° C. rise is allowed. The proper determination of heating in electrical apparatus is by resistance measurements, as stated in Chap. XVII.

It is important to locate the heat where it is produced. A hot bearing may cause the armature or commutator to heat, or *vice versa;* hence all parts should be tested, to ascertain which is the *hottest.* It is more definite to start with the machine perfectly cool, and any serious trouble is usually perceptible after a few minutes' run at full speed with the field-magnet excited.

HEATING OF COMMUTATOR AND BRUSHES.

1. **Cause.** — *Heat produced in the armature, bearing, or field-coils.*

2. *Sparking.* — Any of the causes of sparking already given will produce heating.

3. *Tendency to spark,* or slight sparking not visible.

4. *Overheated commutator* may disintegrate carbon brushes, and cover commutator with a black film which offers resistance and aggravates the heat.

5. *Bad connections in brush-holder.*

6. *Arcing or short circuit in commutator* across mica, or insulation between bars or nuts.

7. *Carbon brushes heated by the current.* — Carbon brushes require less attention than copper, because they do not "cut"

* *Electric Power*, June, 1895.

the commutator, and their resistance prevents the development of sparking; but this higher resistance causes them to heat more than copper, particularly if they do not make good contact over their entire surface.

HEATING OF ARMATURE.

If the armature of a dynamo is allowed to run as a motor without load, any excess of current taken must be converted into heat by some defect; hence this current is the best indication of the condition of a machine. It is easy to determine whether an armature is hot, even when running, by placing the hand in the current of air thrown off by centrifugal force.

1. **Cause.** — *Excessive current in armature coils.* — The same as Cause 1 for Sparking.

2. *Short-circuited armature coils.* — The same as Cause 5 for Sparking.

3. *Moisture in armature coils.* — Similar to preceding, but armature is more uniformly heated, and gives off vapor. Should be baked for several hours at about 240° F. This may be done in an oven, near a fire, or by passing full current through it.

4. *Foucault currents in armature core.* — This is a matter of first construction. (See Chapter XVII.)

5. *Eddy currents in armature conductors.* — Also structural. (See Chapter XVII.)

6. *Reversed coils on one side of armature,* which cause a local current to circulate around it. A small current is sent through the armature standing still, and faulty coil will show reversed polarity if a compass is slowly passed around the armature.

7. *Heat conveyed from other parts.* (See Heating of Commutator, Bearings, and Field.)

8. *Flying short circuit between armature conductors,* which only exists while armature is running, and is usually due to centrifugal force.

HEATING OF FIELD—MAGNETS.

1. **Cause.** — *Excessive current in field-coils.* — Reduce the voltage, or increase the resistance, of a shunt-field. If the trouble is due to a short circuit in one coil, that one will be cooler, and

the corresponding pole-piece will be magnetically weaker, than the others with which it is in series.

2. *Foucault currents in pole-pieces.* — A structural defect. (See Chapter XVII.)

3. *Moisture in field-coils.* — Similar effect to Cause 1. Treatment as in Cause 3 for Armature Heating.

HEATING OF BEARINGS.

If the bearing is very hot, the shaft should be kept turning slowly, as it might "freeze," or stick fast, if stopped.

1. **Cause.** — *Lack of oil.*
2. *Grit or other foreign matter in the bearings.*
3. *Shaft rough or cut.*
4. *Shaft and bearing fit too tightly.*
5. *Shaft sprung or bent,* in which case it turns with more difficulty at a certain part of its revolution.
6. *Bearings out of line.* — Shaft turns more easily if screws which hold bearing in place are slightly loosened.
7. *Thrust of pulley, collar, or shoulder on shaft against one or both of the bearings.*
8. *Too great strain on the belt.*
9. *Armature nearer one pole-piece, producing greater magnetic attraction on that side.*
10. *Bearing is heated by hot pulley, commutator, or armature.*

NOISE.

A dynamo may seem to make a noise, which in reality is caused by the engine or other machinery to which it is connected, but listening near the different parts will show where the sound originates.

1. **Cause.** — *Vibration due to armature or pulley being out of balance.* (See Chapter XVII.)

2. *Armature strikes or rubs against pole-pieces.* — This is detected by placing the ear near the pole-piece, by examining the armature to see if its surface is abraded, or by observing the clearance between the armature and field while the former is slowly revolved.

3. *Shaft collar or shoulder, hub or edge of pulley, or belt, strikes against bearings.*

4. *Rattling due to looseness of screws or other parts.*

5. *Humming, squeaking, or hissing of brushes.* — May be located by placing the ear near the commutator, and by lifting off the brushes one at a time. A little oil usually reduces the noise; but a rough commutator should be made smooth, as described under Cause 3 of Sparking.

6. *Flapping of belt or pounding of joint against pulley.*

7. *Slipping of belt on pulley because of overload,* producing an intermittent squeaking noise.

8. *Humming of armature teeth as they pass edges of pole-pieces.*

9. *Humming due to alternating or pulsating current.*

SPEED TOO LOW.

1. **Cause.** — *Overload.* (See Cause 1, Sparking.)

2. *Short circuit in armature.* (See Cause 5, Sparking.)

3. *Armature strikes pole-pieces.* (See Cause 2, Noise.)

4. *Shaft does not revolve freely.* (See Heating of Bearings, all cases.)

FAILURE TO GENERATE.

1. **Cause.** — *Residual magnetism too weak or destroyed,* due to (*a*) vibration or jar; (*b*) proximity of another dynamo; (*c*) earth's magnetism; (*d*) accidental reversed current through fields, not enough to completely reverse magnetism. Actual reversal of residual magnetism may be very objectionable, as in case of charging storage batteries; but, although the popular supposition is to the contrary, it will not cause the machine to fail to generate.

2. *Reversed connections or direction of rotation.*

3. *Short circuit in the machine or external circuit* prevents the voltage of a shunt-wound dynamo from building up.

4. *Field-coils opposed to each other,* in which case the pole-pieces will be of the same instead of opposite polarity when tested with a compass, a current from some other source being sent through the coils.

5. *Open circuit.* — (*a*) broken wire or faulty connection in the dynamo itself; (*b*) brushes not in contact with the commutator;

(*c*) safety-fuse melted or absent; (*d*) switch open; (*e*) external circuit open.

In all the other cases when a dynamo fails to generate, the field-magnetism is very weak; but it sometimes happens that the magnetism may have full strength, and the only trouble is the simple fact that a switch or other connection is open. This is determined by testing the field-magnets with a piece of iron.

6. *Brushes not in proper position.* — The correct points of contact for the brushes depend upon the particular kind of winding, and no general rules can be laid down. In the absence of definite knowledge, the points on the commutator having the greatest difference of potential, as determined by a voltmeter, are the proper positions for the brushes.

Bibliography of the Dynamo-Electric Machinery.—A number of important papers and articles on this subject have already been referred to in the last four chapters. Among the prominent books relating to the dynamo are the following:—

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CHAPTER XX.

STORAGE BATTERIES. PRINCIPLES, CONSTRUCTION, AND MANAGEMENT.

STORAGE or secondary batteries, also called accumulators, consist of cells in which a chemical change is brought about by passing an electric current through them, thereby rendering them capable of giving back electrical energy by discharging them until they return to their original chemical condition.

Ordinarily a storage battery consists essentially of two sets of plates immersed in a chemical solution. The plates are of metal or metallic compound, and the solution is incapable of acting upon them until an electric current is passed from one plate to the other. This current decomposes the electrolyte; one of its constituent elements or radicals goes to one plate, and the remaining constituent to the other, so that when the passage of the current ceases there are two chemical elements or radicals with a tendency to unite, and upon combination the energy evolved appears as an electric current, which flows in a direction opposite to that of the charging current. The flow of current continues until the cell is restored to its original condition; when this occurs the cell is said to be discharged and must be charged again or regenerated by passing a current through it, as before.

A Primary Cell is one in which electrical energy is produced by the chemical action of one or two solutions on the plates of the cell. When the solutions or plates or both are exhausted, they are replaced by new ones and are *not* restored to their original condition by the passage of an electrical current. The ability to be electrically regenerated, known as *reversibility*, is the fundamental difference between storage and primary cells.

In 1802, soon after the invention of the primary cell by Volta, Gautherot demonstrated the fact that platinum wires, after being used to electrolize saline solutions, were abie to produce secondary currents. Volta, Ritter, Davy, and others noted similar effects,

the phenomenon being what is commonly called polarization. In 1859 P.anté under ook a series of experiments with the object of magnifying this effect and finally developed the Planté type of storage battery; nearly all successful types of the present day being based upon it.

Types of Storage Batteries:

Planté.
Faure.
Combination of Planté and Faure.
Non-lead.

PLANTÉ BATTERY.

This cell was originally made by placing two plates of metallic lead in a vessel containing dilute sulphuric acid. These plates were connected to an electric generator, and a current sent through the cell, which decomposed the electrolyte and oxidized the positive plate. The cell was then discharged; but the energy obtained was very small, the action being confined to the immediate surface of the plates. By repeated charging and discharging first in one direction and then in the other, the oxidation penetrated deeper and deeper into both plates, thus increasing the storage capacity of the cell.

The chief difficulty with the Planté battery was the great length of time required for "forming" the plates, which as just explained consists in converting the surface of the plates into active materials by repeated charging and discharging. This takes a long time and is expensive, as it requires a large consumption of electrical energy. Planté hastened this forming process by pickling the plates in dilute nitric acid, then washing them in a 10 per cent sulphuric acid solution, after which they were electrically formed.

In 1881 Faure devised the method of pasting the lead oxide or active material directly upon the plates. This largely avoids the tedious forming process; but the plates thus produced are not as durable as the Planté elements, being more likely to disintegrate and buckle, because the paste is not an integral part of the plate and there is considerable difference in the coefficients of expansion of lead and of the oxide.

General Principles of the Storage Battery.—Any primary battery will act as a storage battery provided its chemical action is reversible. The ordinary gravity cell, for example, may be regenerated by sending a current through it in the direction opposite

to that of the current produced by it. The zinc sulphate and the metallic copper are thus reconverted into metallic zinc and sulphate of copper respectively, the chemical action being

$$ZnSO_4 + Cu + \text{Electricity} = Zn + CuSO_4,$$

which is exactly the reverse of the action in the primary cell. There are, however, practical difficulties in the continued recharging of a spent gravity cell, due to the ultimate mixture of the sulphate solutions, so that the copper salt reaches the negative electrode, where the metal is deposited and sets up destructive local action. In some forms of primary cells, the chemical action liberates a gas that escapes, so that the action is irreversible.

Chemical Action in Lead Storage Batteries.—The exact nature of the chemical changes which occur in lead batteries is not yet fully established. Planté believed the charging action to consist in the formation of peroxide of lead (PbO_2) on the positive plate, and metallic lead on the negative, which were converted into lead oxide (PbO) on both plates by the discharge. Some authorities still maintain this to be the chief reaction; but it has been shown by Gladstone and Tribe,* and corroborated by subsequent investigations, that the formation of lead sulphate plays an important part.†

The principal reaction may be represented as follows:—

	Positive Plate.		Electrolyte.		Negative Plate.
Charged Condition	PbO_2	+	$2H_2SO_4$	+	Pb
Discharged "	$PbSO_4$	+	$2H_2O$	+	$PbSO_4$
Charging Current		$\longrightarrow$			
Discharging "		$\longleftarrow$			

According to the above equations, the active material on both plates is converted into lead sulphate when the battery is discharged. The reasons for believing this to occur are: *first*, chemical analysis shows that lead sulphate exists in the discharged plate; *second*, the density of the electrolyte decreases during the discharge of the cell, corresponding to the consumption of sulphuric acid and the formation of water as shown in the above reactions; *third*, on thermochemical grounds, the energy produced by the formation of

* *Nature*, Jan. 5, March 16, July 13, Oct. 13, 1882, and April 19, 1883.

† *Electrician* (Lond.), beginning Sept., 1894; also *Electricity* (N. Y.), beginning Oct. 10, 1894, by E. J. Wade. *Journal Institution of Elect. Eng.*, vol. xix., by W. E. Ayrton.

lead sulphate from metallic lead and the peroxide corresponds with the *E.M.F.* obtained.

Storage Batteries of the Planté Type.—It was noted that the serious objection to the Planté battery was the great length of time necessary to form the plates, and how Planté treated them with nitric acid to hasten this action. Other methods are used to obtain a quickened formation, and are tabulated as follows:—

1. *Mechanical Action:* Laminated plates, made up of lead ribbons or built up of lead wires, etc. The surface of the plate is grooved with some forming tool.
2. *Chemical:* Treating the plates in some pickling bath, to produce initial oxidation.
3. *Electrolytic:* Forming a plate of some compound of lead or an alloy, and either reducing the compound or eating the foreign matter away, leaving a porous lead plate.

The Gould Storage Battery.—This battery is made by the Gould Electric Storage Battery Company, and the plates are produced by a combination of the first and third methods. The plates or blanks are placed in steel frames and passed between two revolving shafts which carry disks that cut the surface as shown in Fig. 162.

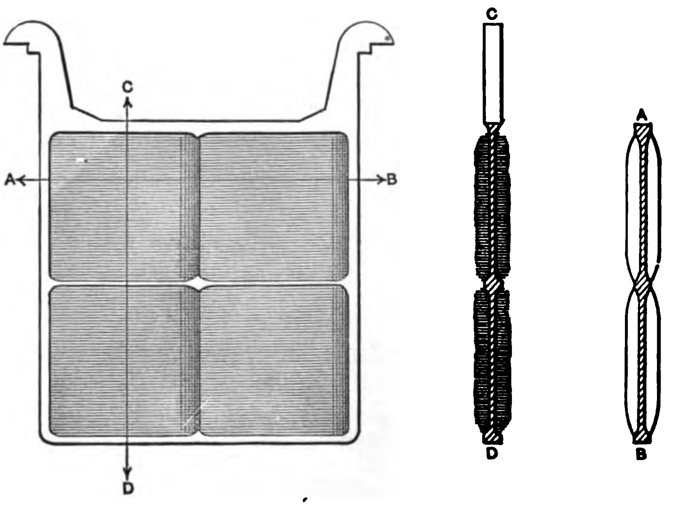

Fig. 162. Gould Storage-Battery Plate.

No lead is removed by this process, but the surface is ploughed up. It is then subjected to electrochemical treatment to form the active

material. The completed cells range in size from a cell of three plates 3 by 3 inches to one of one hundred and five plates 15.5 by 31 inches, and in capacity from 5 to 17,000 ampere-hours.

The Bijur "High-Duty" Battery.—This battery manufactured by the General Storage Battery Co., employs plates of the Planté type, the difference between the two elements being in the design of the grills, or units, which compose them (Fig. 163). The positive plates have an excess of lead for future oxidization, while the negatives have sufficient only for mechanical strength and electrical conductivity.

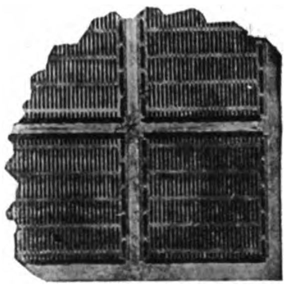

Fig. 163. Bijur Battery Grills.

This battery is distinguished by the fact that the units are made separately and then welded by a special process into a solid framework of lead-antimony alloy, or pure lead; the former being generally employed on account of greater mechanical stability. These units are so held in the frame that they allow of expansion in all directions; thus they are not likely to set up strains and the tendency towards buckling is avoided. The grills are opened throughout so that one can look through a plate. This feature permits of free circulation of the electrolyte. On this account, and because the oxide is in a thin and dense layer, formed on the grill electrochemically, injurious sulphate can be readily removed by a series of charges and discharges. The design affords an unusually high capacity due to the great amount of oxide and surface exposed in a given size of plate. This battery is particularly suitable where it cannot receive careful handling or when likely to be subjected to high rates of charge and discharge.

Faure Types of Storage Battery.—The difficulty with the Faure type is the tendency to disintegrate or buckle. Various means intended to increase the adhesion of the active material have been suggested, of which the most important are as follows:

1. Plates are grooved, roughened, or "pocketed."

2. Plates are perforated, the holes being circular or rectangular and varying in cross-section as shown in Fig. 164.

3. The active materials may be inclosed in either a conducting or a non-conducting cage.

4. The plates may be made up entirely of active material.

Faure cells usually have a greater output for a given weight,

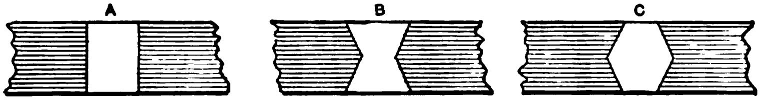

Fig. 164. Different Cross-Sections of Faure Plate Perforations.

that is, a higher weight efficiency, than Planté types, because the proportion of active material may be made larger.

The E. P. S. Battery is one of the most important of the Faure type, its name being the initials of the Electric Power Storage Company, by which it is manufactured in England.

The plates consist of lead grids cast in an iron mold, and have the cross-section shown in Fig. 165. The later types have a thin

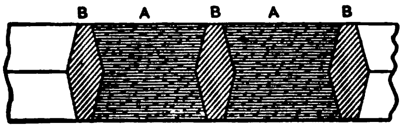

Fig. 165. E. P, S. Battery Plate.

perforated strip of lead running across each opening midway between the edges. The holes *A* in the grid are completely filled with a paste of red lead or minium (Pb_3O_4) and dilute sulphuric acid for the positive, while the paste for the negative consists of minium, or litharge (PbO) and dilute sulphuric acid or magnesium sulphate solution. These pastes are pressed into the grids and dried. The plates are hardened in dilute sulphuric acid, after which they are ready for forming. A strong current for 48 hours is required for the positive plate and for 24 hours in the case of the negative plate.

COMBINATIONS OF PLANTÉ AND FAURE TYPES.

The Chloride Battery, manufactured by the Electric Storage Battery Company of Philadelphia, is a compromise between the Planté and Faure types, the positive being of the Planté type and the negative of practically the Faure type.

The principal features in the manufacture of this battery are as follows: The first step is the production of finely divided lead.

which is made by directing a blast of air against a stream of the molten metal, producing a spray of lead which upon cooling falls as a powder. This powder is dissolved in nitric acid (HNO_3) and precipitated as lead chloride ($PbCl_2$) on the addition of hydrochloric acid (HCl). This chloride washed and dried forms the basis of the material which afterwards becomes active in the negative plate *B*, Fig. 166. The lead chloride is mixed with zinc

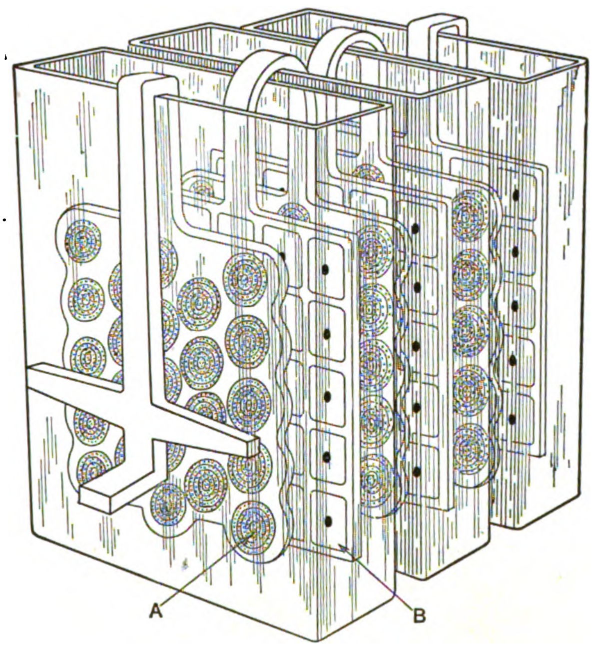

Fig. 166. The Chloride Battery.

chloride, and melted in crucibles, then cast into small pastiles or tablets about $\frac{3}{4}$ inch square and of the thickness of the negative plate, which according to the size of the battery varies from $\frac{1}{4}$ inch to $\frac{5}{16}$ inch. These tablets are then put in molds and held in place by pins, so that they clear each other by .2 inch and are at the same distance from the edges of the mold. Molten lead is then forced into the mold under about seventy-five pounds pressure, completely filling the space between the tablets. The result is a solid lead grid holding small squares of active material. The lead chloride is then reduced by stacking the plates in a tank containing a dilute solution of zinc chloride, slabs of zinc being alternated with

them. This assemblage of plates constitutes a short-circuited cell, the lead chloride being reduced to metallic lead. The plates are then thoroughly washed to remove all traces or zinc chloride.

A later form of negative plate consists of a "pocketed" grid, the opening being filled with a litharge paste; this is then covered with perforated lead sheets, which are soldered to the grid. The positive plate (*A*, Fig. 166) is a firm grid, composed of lead alloyed with about 5 per cent of antimony, about $\frac{7}{16}$ inch thick, with circular holes $\frac{25}{32}$ inch in diameter, staggered so that the nearest points are .2 inch apart. Corrugated lead ribbons $\frac{25}{32}$ inch wide are then rolled up into close spirals of $\frac{25}{32}$ inch in diameter, which are forced into the circular holes of the plate. By electrochemical action these spirals are formed into active material, the process requiring about thirty hours; at the same time the spirals expand so that they fit still more closely in the grids. This form of positive is known as the Manchester Plate.

In setting up the cells the plates are separated from each other by special cherry wood partitions, the perforations being connected by vertical grooves to facilitate the rising of the gases. Sometimes glass rods are used as separators.

There are ten sizes of cell, the smallest containing three plates 3 by 3 inches, and the largest having seventy-five plates 15½ by 30¾ inches, ranging in capacity from 5 to 12,000 ampere-hours, and in weight from 5½ to 5,800 lbs. The smaller sizes are provided with either rubber or glass jars, and the larger ones with lead-lined tanks.

The Tudor Cell is extensively used in Europe, and to some extent in this country, although no longer manufactured here. The plates consist of rolled, grooved sheets as shown in Fig. 167, *A* being the hollows or grooves into which the paste is introduced and *B* the lead frame. The thickness of the plate between opposite grooves is about .12 inch for the positive, and about .06 inch for the negative. The width of grooves on the positive plate is also about .12 inch, while on the negative it is about .08 inch. The grooves are first coated with a thin layer of peroxide of lead (PbO_2) by electrolysis, and then packed with the oxides as required, the plates being rolled to "fix" the paste. This treatment of the grid with an electrolytic bath before applying the active material is covered by U. S. patent No. 413,112. The cells, of this type, range in capacity from 26 to 630 ampere-hours.

It is the tendency to make the positive plate of the Planté form and the negative of the Faure or pasted type, the reason being that the Planté form is more difficult to make, and as the activity is small on the negative, the pasted plate is good enough. The practice in lead batteries is to make the negative plate of greater capacity than the positive, as the charging and discharging of a cell in service tends to form more active material on the positive plate, whereas the capacity of the negative plate tends to decrease, so that allowance is made as above stated.

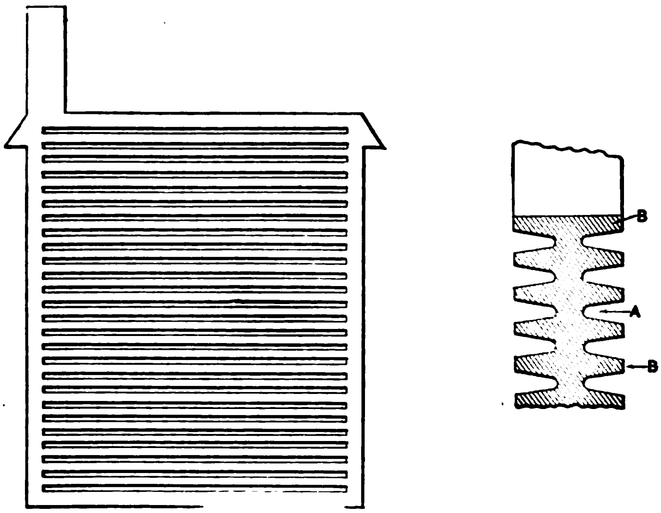

Fig. 167. Tudor Battery Plate.

Lithanode.—Mr. Desmond Fitzgerald has made storage batteries with a positive plate consisting entirely of active material made up of litharge (PbO) mixed with ammonium sulphate $(NH_4)_2SO_4$ pressed into the required shapes. This plate is converted into peroxide by chemical treatment. The negative consists of the ordinary lead plate. While this cell has a high weight efficiency, it is not of much commercial importance, though used considerably in laboratory work.

Storage Batteries Containing Metals other than Lead.—It has already been stated that almost any primary cell will act more or less perfectly as a secondary cell; as, for example, the common gravity battery. A great many have been devised in which the lead in one or both of the plates has been replaced by some other metal.

For example, Reynier made the negative plate of zinc instead of lead, this zinc in discharging being converted into zinc sulphate, which dissolved in the electrolyte. The substitution of zinc for lead secures an increase in initial *E.M.F.* from 2.2 to 2.5 volts, and also allows of a considerable reduction in weight; because for the storage of a given amount of energy the weight of the zinc required is much less than that of the equivalent lead. A difficulty with this type of cell is the formation of "trees" of zinc on the negative plate during the charging process, which are likely to fall off or extend across to the positive plate, thus short-circuiting the cell. Another difficulty is the difference in density of the solution between the top and bottom of the plates, the tendency being to exhaust the zinc sulphate from the upper portion of the liquid during charging. To avoid this trouble the plates have been arranged horizontally, so that the density would be uniform for each plate; but the difficulty then arises that the gases which form to a certain extent in almost all batteries collect between the plates, interfering with the chemical action and the passage of the current.

A similar type of cell was manufactured by the Union Electric Company of New York, in which the negative plates consisted of thin sheet copper covered with zinc amalgam, and the positive plates were made up of laminæ of lead held together by leaden rivets and perforated with numerous small holes, these positives being formed by the Planté process.

Waddell-Entz Accumulator.—The copper-alkali-zinc primary battery of Lalande, Chaperon, and Edison, being reversible in action, can be used as a storage-battery. Waddell and Entz have constructed accumulators on this principle. When discharged, the positive plate consists of porous copper; on charging the electrolyte is decomposed, metallic zinc being deposited on the negative plate, the porous copper of the positive plate is oxidized, and the liquid becomes converted into a solution of caustic potash (KOH). The *E.M.F.* is low, being about .7 volt per cell.

The Edison Storage Battery.—The standard cells of this type are 13 inches high, 5.1 inches wide, and vary in length according to their rating, the various capacities being obtained by simply increasing the number of plates. The positive and negative plates are alike in appearance, and consist of rectangular grids, of nickel-plated iron, each about 9½ by 5 by .025 inch, punched with three rows of

rectangular holes, eight holes to the row (Fig. 168); each hole being filled by a shallow perforated box of nickel-plated steel, the perforations being very fine, about 2,500 per square inch.

The difference between the positive and negative plates is entirely in the contents of the perforated receptacles; those for the

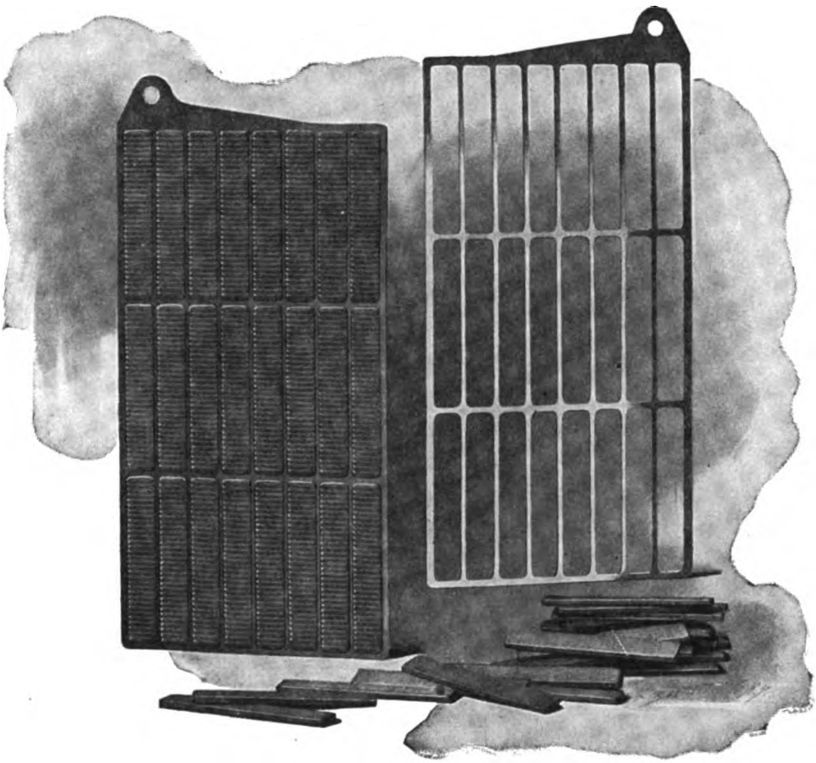

Fig. 168. Edison Battery Grids.

positive plate containing a mixture of oxide of nickel and pulverized carbon, the latter being employed to increase the conductivity of the active material. The receptacles for the negative plates contain a finely divided oxide of iron and pulverized carbon. When filled these receptacles are secured to the grid by placing them in the openings of the same, and subjecting the assembled plate to a pressure of about 100 tons, which expands the pockets and fixes them firmly in the grid, the assembled plates being shown in Fig. 169.

The liquid employed consists of a 20 per cent solution of caustic

potash, which undergoes no chemical change during the process of charge or discharge, acting simply as a conveyor of oxygen between the plates. The charging current, entering at the positive plates, oxidizes the nickel compound to the peroxide state, and reduces the iron compound in the negative plates to a spongy iron mass. The con-

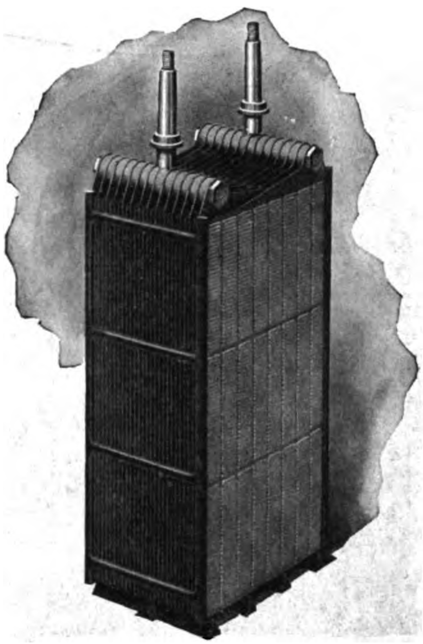

Fig. 169. Complete Edison Cell.

taining vessel consists of nickel-plated steel, and the plates are strong individually and close together, being separated by thin strips of vulcanized rubber, thus forming a compact mass. The terminals of the plate pass through the cover of the cell, from which they are insulated by vulcanized rubber bushings.

The electrical features of the Edison cell are as follows:—

Average voltage of charge at normal rate, 1.68.

Average voltage of discharge at normal rate, 1.24.

A set of charge and discharge curves of a 180-ampere-hour cell is shown in Fig. 170. This battery is rated at 30 amperes for a period of six hours. The various cells have a weight efficiency of 11.5 to 13.2 watt-hours per pound, depending upon the size. The watt efficiency under normal working conditions is about 60 per

cent. The charging and discharging rates are alike and cover wide ranges. A cell may be charged at a high rate in one hour, without apparent detriment except lowering the efficiency slightly. It is not appreciably influenced by temperature changes, and may be fully discharged to the zero-point of *E.M.F.*, or even charged in the reverse direction, and then recharged to normal conditions without suffering loss in storage capacity or other injury. The best

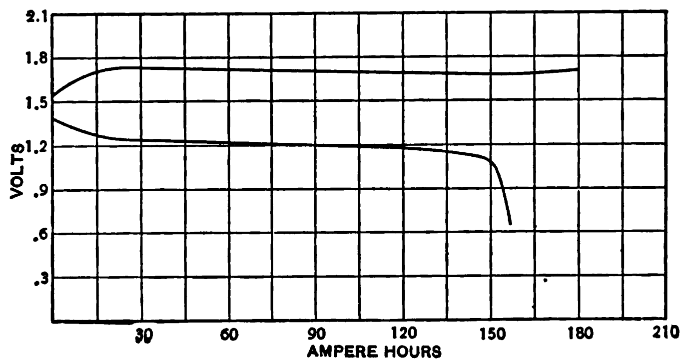

Fig. 170. Charge and Discharge Curves of Edison Cell.

results are obtained when twice as many positive as negative plates are employed, and the standard cells are made up on this basis. This type is intended especially for electric automobile service, by virtue of its high weight efficiency, and ability to endure rough mechanical as well as electrical treatment. The same qualities would also adapt it to portable electric-lighting purposes.

MANAGEMENT OF STORAGE BATTERIES.

In describing the handling of storage batteries, the various types of lead cells will be considered, as they constitute a very large majority of the cells in commercial use, especially for stationary service.

The Battery Room.—In the installation of a battery, the first point to be considered is its location. The room for this purpose should be dry, well ventilated, and of a moderate temperature, otherwise the evaporation of the electrolyte will be excessive. The floor, walls, and ceiling must be of some acid-proof material, brick or tile being preferable, and the floor made so as to drain readily;

an outlet being provided to the sewer or drainage system. If the room is an old one, having a wooden floor, the latter should be coated with asphaltum paint, and lead trays placed below the batteries; any woodwork or ironwork in the room should also be treated in a similar manner.

The room should be sealed from the rest of the building, and located near the generating machinery and distribution switchboard, so that the copper cables may be low in cost. The windows in the battery room should be either of ground or painted glass, so that no direct rays of the sun may strike the cells, as the heat may crack the cells if made of glass, or increase the activity of the acid, which is not desirable.

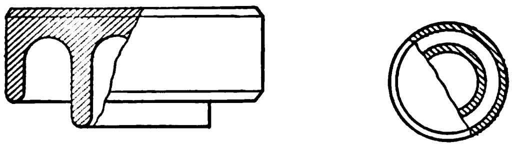

Fig. 171. Glass Insulator for Battery Support.

In case the battery installation is in a cold climate, some device for keeping the electrolyte at a moderate temperature must be used. A simple plan is to suspend an incandescent lamp in the cell and have it connected to some automatic device which will put it out when the electrolyte is at the desired temperature, or light it when the electrolyte is too cold.

Setting up the Cells.—The battery is usually placed on the floor, or upon strong wooden shelves; Fig. 172 showing a form adapted to cells of medium size. Iron stands are sometimes used for large and heavy cells, but they must be protected from acid fumes and drip by several coats of an acid-proof paint. Wooden stands should be varnished, painted, or soaked in paraffin for the same reason. It is important to have every cell accessible for inspection, cleaning, and removal, it being desirable to reach both sides. There should also be sufficient head room between shelves so that the elements may be lifted out.

It is highly important that the cells be thoroughly insulated from each other, to avoid leakage of current. This is accomplished by standing each cell on four insulators of porcelain or glass of the design shown in Fig. 171. Porcelain is preferable to glass, as the latter is sometimes pitted by the action of acid fumes.

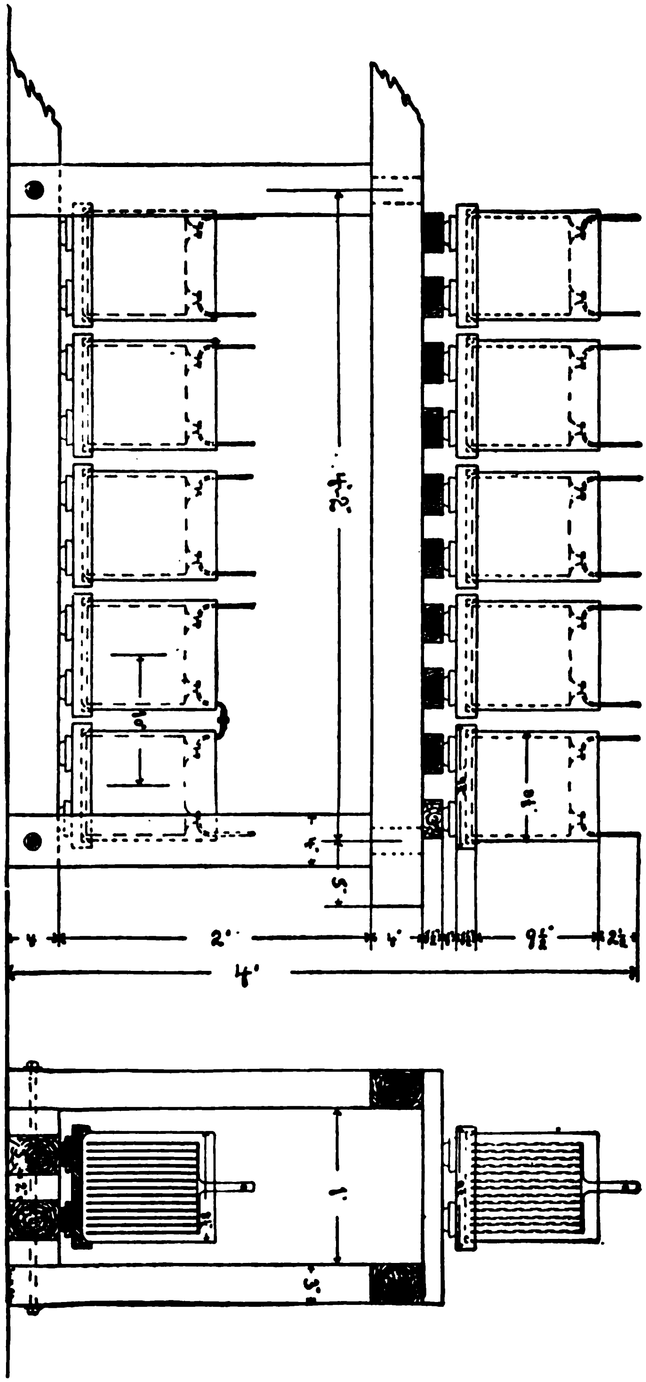

Fig. 172. Wooden Battery Stand.

Lead-lined tanks are usually set as follows: The floor is covered with a layer of glazed tile or brick, on which are placed two wooden stringers about 3 by 4 inches, carefully painted with acid-proof paint. On these are set four insulators held in place by wooden pegs kept in position by pouring melted sulphur around them. The battery tray and battery are placed on these insulators as indicated in Fig. 172.

Oil insulators were formerly used, but the oil collects dust, and as this is likely to cause leakage they are no longer employed. For very large lead-tank outfits a double system of the supporting construction shown in Fig. 172 is used, but with individual stringers for each cell. Glass cells are often set on wooden trays, which are filled with sand to distribute the strains and absorb the drip. Sawdust was also used, but it becomes carbonized by the acid drip, and as this is likely to cause leakage, it has been abandoned.

In connecting the cells, usually put in series, great care should be taken to join the positive terminal of one to the negative of the next, and so on. The color of the plate is the best indication of its polarity, the positive plate being a light brown when discharged and a chocolate color when charged, while the negative varies from a dark to a light slate color. It should be noted that the nomenclature concerning storage batteries is different from that of primary cells. The positive plate in the former is the peroxide plate (brown) and is that one from which the current flows out in discharging, whereas that would be the negative plate of a primary battery. The positive pole or terminal in a storage battery is an extension of the positive plate, and is connected to the positive terminal of the dynamo in charging; consequently there is less cause for confusion of terms than with the primary cell.

It is well to test the polarity of each cell and of the circuit before making connections. This may be done with any form of pole-tester, or by the definite expedient of dipping the two terminals in dilute sulphuric acid, the one from which the most bubbles arise being negative. The connections should be scraped clean and screwed up very tight, being coated with acid-proof paint to avoid corrosion. The most satisfactory way is to weld or "burn" the positive terminal of one cell to the negative terminal of the next, though soldered connections are good. This soldering is done as follows: Two strips of lead and the terminals to be connected are very

carefully cleaned; the lead strips are then clamped to the terminals, a mold placed around the joints and molten lead poured into it.

The Electrolyte.—Practice varies considerably as to the strength of solution to use. Chemically pure sulphuric acid is carefully poured into water until its density becomes about 1.2, and then the mixture is allowed to cool before pouring it into the cells. It is important to use perfectly pure acid and water, as impurities will cause local actions and ultimately destroy the plates. Water should never be poured into sulphuric acid, as it is likely to cause the liquid to be thrown out violently. The electrolyte should completely cover the plates. Cells for vehicle work use an electrolyte with density as high as 1.3. The advantage of a strong solution is its lower resistance; but it is likely to produce the very objectionable effect of "sulphating."

The density of the electrolyte falls immediately after filling a cell, some of the acid being taken up by the plates; but it rises again in charging; for example, from 1.17 to 1.2. It is convenient to keep hydrometers in several cells to observe the density of the electrolyte, not only at the beginning, but as a permanent indicator of the amount of charge and general working conditions.

Charging.—The charging should begin immediately after a new cell is filled with the electrolyte, otherwise the plates are likely to become "sulphated." The first charge differs from subsequent regular charges in that it should be at a rate (lower than normal) that will not cause the temperature of the cell to reach 100° F., but in all other respects it is the same.

Indications of Amount of Charge in a Storage Battery.—1. *The E.M.F.* rises from 1.7 volts, the minimum value to which a lead cell should be discharged, to approximately 2.5 volts when fully charged, although this value may be a trifle higher or lower, depending upon the rate of charge and temperature of cell. The rise is gradual, but more rapid near the beginning and end of the charge, as indicated in Fig. 173. When the cell is fully charged, the *E.M.F.* becomes constant and the curve approaches a horizontal line as shown. The charging should then be stopped, as any more energy passed through the cell is simply wasted in producing gases. The external voltage is higher in charging than in discharging because of the internal resistance of the cell and resulting drop, which must be overcome in charging. The voltage

should be measured when the current is flowing either in charging or discharging. The *E.M.F.* on open circuit has lit le practical significance. The exact electrical relations are given later.

2. *If a record is kept* of the exact number of ampere-hours of charge and discharge, the actual amount of energy in the battery

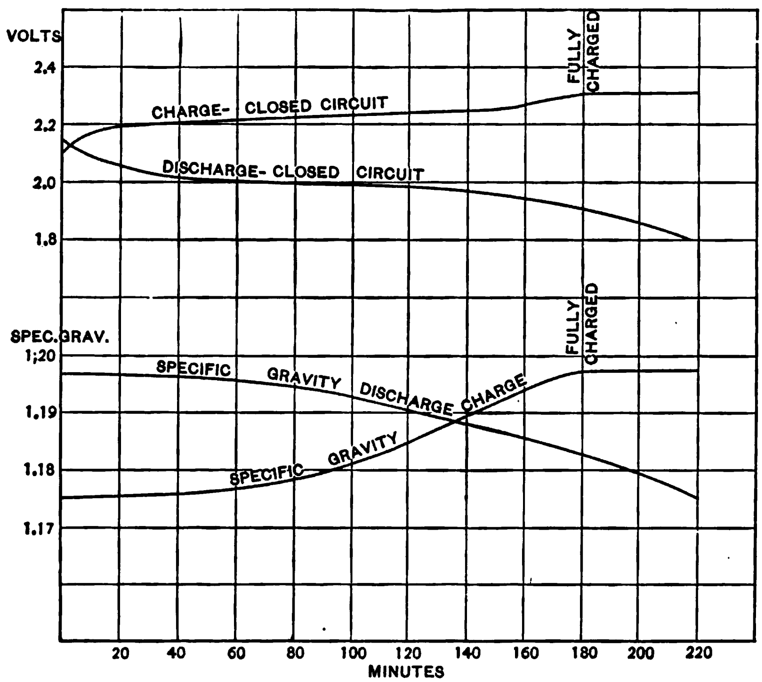

Fig. 173. Curves showing Variations in Specific Gravity and Voltage in a Lead Storage Battery during Charge and Discharge.

at any time is known, due allowance being made for leakage and other losses. For this purpose any integrating instrument, such as the Thomson recording wattmeter, may be used.

3. *The density of the electrolyte* gradually rises during the charging operation (Fig. 173); the density when charged being about .025 higher than when discharged. There is a lag in the change of the density of the electrolyte, the acid not being absorbed or given off at once by the plates; hence a little time should be allowed before taking any hydrometer reading as final.

4. *Bubbles of gas are given off* freely when the battery is fully charged, because the material of the plates is then no longer able

to take up the oxygen and hydrogen which tend to be set free by the electrolysis; these bubbles give the electrolyte the appearance of boiling, and often they are so fine that the liquid looks almost milky-white, particularly in a cell which has not been very long in use.

5. *The color of the positive plates* varies from a light brown on active parts to a chocolate color when fully charged, and to nearly black when overcharged. The negatives vary from pale to dark slate color, but they always differ in color from the positives. This indication of the amount of charge is learned by experience, but is quite definite after one becomes familiar with a particular battery.

6. *Cadmium Test.*—Cadmium, when immersed in the electrolyte of a storage battery, gives reliable readings of the potential of the positive and the negative plates with respect to itself. In this way the condition of each plate of a battery can be determined. Readings are taken by inserting the cadmium (connected to one terminal of the voltmeter) into the electrolyte, but free from contact with plates, and connecting the other terminal of the voltmeter first to the positive plate, and then to the negative plate.

In making a cadmium test, care must be exercised to use either a sulphated piece of cadmium, or to wash the surface of the bright metal, after every reading, in distilled water, also when inserting the cadmium into the electrolyte, to keep it out of contact with the plates. The cadmium piece can be permanently fastened to one terminal of the voltmeter, and it should be covered by a soft rubber tube, perforated to admit the electrolyte; in this way rapid reading can be taken.

The relations between the cadmium readings and the total external voltage of the cell is fixed, that is to say, on discharge, the latter added to the minus (cadmium to negative plate) reading should equal the plus (cadmium to positive plate) reading. The voltmeter used for this work ought to be a good one and read accurately at the low end of the scale, otherwise the minus readings cannot be taken.

With normal conditions of cell, when fully charged and on open circuit, the difference of potential between the positive plate and the cadmium piece is 2.5 volts or nearly so, and between the cadmium piece and the negative plate is zero or nearly so.

To avoid false conclusions in making a cadmium test, hydrometer, temperature, and charge data should be noted. The cadmium test is usually made at the center of the cell to get a uniform current distribution. This test gives readings the sum of which is less than 2.5 volts, when hydrometer tests, temperature, and charge data show that the cell is not fully charged. If, however, the hydrometer, temperature, and other data show the charge to be completed, and the cadmium test gives .1 volt or more below 2.5 volts, it indicates trouble; whichever plate shows the falling off from normal reading is the defective one, and should be examined for some of the troubles that will be discussed later.

In some cases the cadmium reading with respect to both plates may approach zero; this is caused by a short circuit in the cell, which should be found and removed immediately.

The proper rate of charge depends upon the size and type of cell, and is usually specified by the manufacturer in each case, being merely an empirical fact, determined by the construction of the plates. The current for charging is ordinarily obtained from a direct-current dynamo, but any other direct-current source may be employed. The potential required for charging must exceed that of the battery, which, during the operation, acts as a counter *E.M.F.*, the expression being $I=\frac{P-e}{R}$, in which I is the current, P the potential applied to battery terminals, e the counter *E.M.F.*, and R the internal resistance of the cell. Usually P is 5 to 10 per cent greater than e, in order to cause the necessary charging current to flow through the resistance R of the cell. In practice P is regulated until the required charging current I is obtained.

The above equation, put into form of $R=\frac{P-e}{I}$, enables the internal resistance R to be calculated, varying considerably with temperature, and with different states of charge. Another form of the above equation, $e=P-IR$, shows that the true *E.M.F.* of the battery is less than the charging voltage by an amount equal to the product of the charging current and the internal resistance. Conversely, in discharging, the total *E.M.F.* of the cell is greater than the potential difference P between its terminals by the same amount, that is, $e=P-IR$. Hence it is necessary to know I and R, or to measure the voltage when the circuit is open (in which case $I=O$),

in order to find the real *E.M.F.* of cell. This applies to each individual cell as well as to the entire battery.

If the charging voltage *P* be kept constant, it is evident from the above equations that the current *I* will gradually decrease, since the *C.E.M.F.* of the cell steadily rises as shown in Fig. 173. This effect is counteracted somewhat by the fact that the internal resistance *R* also diminishes, owing to the density of the electrolyte increasing. Such a gradual reduction in the strength of the charging current is considered desirable by some authorities, because it enables the cell to take a greater charge than if the current were maintained at full strength. On the other hand, a diminishing rate makes it difficult to keep account of the exact number of ampere-hours supplied to the cell; hence in ordinary commercial work it is considered simpler to charge with a constant current, and if it is desired to keep the cell temperature down, the current may be decreased near the end of the charge. Most types of cells are not injured by slight overcharging at a moderate rate and it may be allowed to occur, because it tends to remove "sulphating." A considerable overcharge should be avoided as it causes excessive formation of gas-bubbles in the active materials, is likely to heat the cell and even cause disintegration and buckling of the plates.

Discharging.—A storage battery is in most cases discharged within a few hours after being charged, as, for example, in electric lighting, when the engine and dynamo are run during the day for charging the battery which supplies current to the lamps during the night. But a portable battery for feeding lamps might be required to retain its charge for several days. A certain loss of charge occurs in any battery, amounting to about 25 per cent in one week, but for one day or less it is quite small. Even when the discharge occurs immediately, the average voltage and the ampere-hours obtained are less than for the charge, as explained under "Efficiency."

The operation of discharging is naturally the converse of charging, the changes which have been described as occurring in the latter take place also in the former, but in the reverse order. The normal rate of discharging is usually equal to that of charging, but may be somewhat greater. In some cases it is necessary to discharge at higher rates, but by so doing a percentage of the capacity in ampere-hours is sacrificed. For example, a cell whose normal

eight-hour discharge rate is 100 amperes can be discharged at 400 amperes for one hour, but only 50 per cent of the cell's capacity in ampere-hours is obtained at the latter rate.

PERCENTAGE OF CAPACITY VARIATION AT DIFFERENT DISCHARGE RATES.

Rate, Hours.	Per Cent of Capacity at Eight-hour Rate.		
	Planté.	Planté + Faure −	Faure.
8	100	100	100
7	99	97	96
6	96½	93½	92
5	93	89	86
4	88	83	80
3	80	75	72
2	70	65	61
1	55	50	46

An excessive discharge rate is injurious to most types of storage-battery plates because it tends to disintegrate the plates, and abnormally heats the electrolyte, which hastens disintegration; it is therefore advisable to protect the battery with fuses or an automatic circuit breaker.

A lead storage battery *should never be discharged completely*, as it is very likely to become "sulphated," or otherwise injured; and moreover the *E.M.F.* falls so rapidly towards the end of discharge that the current would be of no practical value. The limit of discharge is usually considered to be the point at which the external voltage drops to 1.75 volts, though when cells are used at the one-hour rate the limit of discharge is 1.6 volts. The charge usually left in a storage battery is from 10 to 30 per cent of the total capacity, depending on the rate of discharge, but this involves no considerable loss of energy or efficiency, since it remains in the battery each time and the charging begins at that point.

The Efficiency of Storage Batteries.—The efficiency of any apparatus is the ratio between what it gives out and what it consumes. In a storage battery it is the ratio of the amount of discharge to what is required to bring the battery back to its original condition. While this seems extremely simple and definite, there are several opportunities for confusion or quibble.

In the first place, the "ampere efficiency," or more properly

the "ampere-hour efficiency," which is the ratio of the ampere-hours drawn from the battery to the ampere-hours put into the battery, is quite different from the watt-hour efficiency. The latter is the real efficiency, because it considers the energy, and includes the voltage as well as the ampere-hours. Ampere efficiency is interesting as showing the action of a battery, but is not of much commercial importance. It may be used either through ignorance or intention to give a false idea, being often 15 per cent higher than the watt efficiency.

Another difficulty with ampere efficiency is the fact that it is possible to obtain an apparent efficiency of over 100 per cent from a storage battery. Since about 25 per cent of charge is always left in the cell, it is possible to draw out apparently more ampere-hours than were put in, by simply discharging more than usual. The same result may be obtained by fully charging a battery several times, but only partially discharging it each time.

In general practice it has been found that the efficiency of storage-battery plants, when in good condition, varies from 75 to 80 per cent.

Depreciation of Storage Batteries.—The depreciation is claimed to be as low as 5 per cent per annum; in fact, storage-battery installations are often insured and kept in repairs by the makers for 4 to 6 per cent per annum of their total original cost. This figure is as low as the maintenance of the very best steam or electrical machinery. Instances are cited in which storage batteries have required no repairs or renewals for periods of five or even ten years. On the other hand, the life of storage batteries in traction or automobile work has in some cases not exceeded six months. One must be somewhat guarded in accepting low figures for depreciation, because from their nature the plates are very easily injured and difficult to repair. It would be unwise for any one purchasing a battery without the makers guarantee, to allow less than 10 per cent for its annual depreciation, and this does not include interest, taxes, or other fixed charges.

TROUBLES AND REMEDIES.

The most serious troubles which occur in storage batteries are *sulphating*, *buckling*, *disintegration*, and *short-circuiting* of the

plates. These can usually be avoided, or cured by proper treatment if they have not gone too far.

Sulphating.—The normal chemical reaction which takes place in storage batteries is supposed to produce lead sulphate ($PbSO_4$) on both plates when they are discharged, their color being usually light brown and gray, due to the presence of PbO_2 on the positive plate. But under certain circumstances a whitish scale forms on the plates, probably consisting of Pb_2SO_5. Plates thus coated are said to be "sulphated." This term is, however, somewhat ambiguous, the formation of a certain proportion of ordinary lead sulphate ($PbSO_4$) being perfectly legitimate, but the word has acquired a special significance in this connection. A plate is inactive, and practically incapable of being charged, when covered with this white "sulphate," as it is a non-conductor.

The conditions under which this objectionable sulphating is likely to occur are as follows:

(*a*) A storage battery may be overdischarged, that is, run below the limits of voltage specified, and left in that condition for several hours.

(*b*) A storage battery may be left discharged for some time, even though the limits have not been exceeded.

(*c*) The electrolyte may be too strong.

(*d*) The electrolyte may be too hot (above 125° F.).

(*e*) A short circuit may cause "sulphating" because the cell becomes discharged (on open circuit) and during charging it receives only a low charge compared with the other cells of the series. A battery may become overdischarged or remain discharged a long time on account of leakage of current due to defective insulation of the cells or circuit, or the plates may become short-circuited by particles of the active or foreign substances falling between them.

(*f*) By charging at a very low rate, for example, one-thirtieth of normal.

Sulphating may be removed by carefully scraping the plates. The faulty cells should then be charged at a low rate (about one-half normal) for a long period. In this way, by fully charging and only partially discharging the cells to about 1.9 volts at the 8-hour rate, for a number of times, the unhealthy sulphate is gradually eliminated. When the cells are only slightly sulphated, the latter treatment is sufficient without scraping; but with cells that are very badly sul-

phated, the charge should be at about one-quarter the normal rate for three days.

Adding to the electrolyte a small quantity of sodium sulphate, or carbonate, which latter is immediately converted into sodium sulphate, tends to hasten the cure of sulphated plates by decomposing or dissolving the white sulphate. This is not often used, as a cell should be emptied, thoroughly washed, and fresh electrolyte added before the cell can be used again.

Sulphating not only reduces the capacity of lead storage batteries, but also uses up the active material by forming a scale which falls off or has to be removed. It also produces the following trouble:

Buckling, or warping of a plate, may be caused by too great expansion of the active material, which strains the ribs of the containing grid; or by uneven action on the two surfaces; for example, a patch of white sulphate on one side of a plate will prevent the action from taking place there, so that the expansion and contraction of the active material on the other side, which occurs in normal working, will cause the plate to buckle. This might be so serious that it would be impossible to straighten the plate without breaking or cracking it; but, if taken in time, it may be accomplished by placing the warped plate between boards, and subjecting it to pressure in a screw or lever press. Striking the plate is objectionable, because it cracks or loosens the active material; but, if it should be necessary to straighten a plate when no press is available, a wooden mallet may be used very carefully, with flat boards laid under and over the plate. Buckling is caused by an excessive rate of charging or discharging, as well as by sulphating.

Disintegration.—Some of the material may become loosened or entirely separated from the plates, as a result of various causes. The chief of these is sulphating, which forms scales or blisters that are likely to fall off, thus gradually reducing the amount of active material and the capacity of the cell. Buckling also tends to disintegrate the plates. Contraction and expansion of the active material may take place in normal working, and are increased by excessive rates or limits of charging and discharging. This constitutes another cause of disintegration, particularly in plates of the Faure type, containing plugs or pellets of lead paste. The fragments which fall from the plates not only involve a loss of active material, but are also likely to extend across or gather between the plates and cause a short circuit.

The positive plates are far more susceptible to and injured by these troubles than the negatives. The former are also more expensive to make, therefore it is to them that special attention should be directed in the management of storage batteries.

Short-Circuiting may be caused by conditions previously stated, and also by the collection of sediment at the bottom of the containing cell. The short-circuiting caused by the dropping in of foreign matter, or bridging by the active materials, is prevented by the use of glass, rubber, or wooden separators. The short-circuiting of plates by the formation of sediment is prevented, or the chances of it are decreased, by raising the plates so that they clear the bottom of the containing cell. In small batteries this clearance is about an inch; in large cells it is considerable, being about 6 inches, and on account of the weight of large-sized plates they are supported at the bottom by glass frames running lengthwise through the cell, as shown in Fig. 174.

The sediment should be watched carefully, and when it reaches a depth of an inch or more at the center of the cells it should be removed. The usual method is to take out the plates, syphon the electrolyte off carefully, and then flush out the tanks until all the sediment is removed. If syphoning cannot be resorted to, a pump may be used, either of glass or of the bronze rotary type.

Troubles from Acid Spray.—A battery will give off occasional bubbles of gas at almost any time; but when nearly charged, the evolution becomes more rapid. These bubbles, as they break at the surface, throw minute particles of acid into the air, forming a fine spray which floats about. This spray not only corrodes the metallic connections and fittings in the battery room, but is also very irritating to the throat and lungs, causing an extremely disagreeable cough. Glass covers are sometimes placed over cells to prevent the escape of fumes, but this is not advisable as the glass becomes moist and will collect dust, thus forming a conducting surface over the battery.

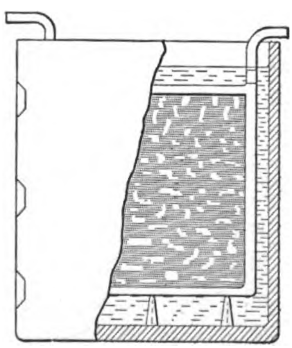

Fig. 174.
Glass-Frame Support Used to Prevent Short-Circuiting by Sediment.

Attempts have been made to do away with the spray by having

an oil film over the electrolyte, but this interferes with the use of hydrometers, and sticks to the surface of the plates when they are removed, thus increasing the resistance when they are replaced. Another plan consists in spreading a layer of finely granulated cork over the surface of the liquid, but while this does not interfere with the hydrometer, it makes the cell look dirty. The general practice is to depend almost entirely upon ventilation to get rid of the acid fumes, in fact, even forced ventilation is used. A blower forces fresh air into the room, which is provided with a free exhaust. In connecting up the cells, it is advisable to use lead-covered copper cables, as this covering protects the copper, and prevents the formation of copper salts which might drop into the cell and contaminate the electrolyte.

The Purity of the Electrolyte is very important, and great care should be taken to insure it. The electrolyte may have nitric acid present when "formed" (Planté) plates are used, and some chlorine, when "Chloride" negatives are used. In addition, iron may be present due to the water or acid, if the sulphuric acid is made from iron pyrites; it may also be present, owing to the corrosion of iron fittings near the cells, some of the scale falling into the electrolyte. Similarly the copper salt formed from the connections by corrosive action may fall into the cell. Mercury may also be present due to the breakage of hydrometers or thermometers. Other foreign substance might be present, but those named are the most harmful.

Nitric acid, even in exceedingly small quantities, causes disintegration, as the supporting metal grid of the plate is destroyed.

Chlorine has a similar effect.

Iron, mercury, and copper produce local action, and thus decrease the efficiency and ultimately the life of the cells.

The electrolyte should be tested about once a week for these impurities, and if any of them are present, it should be drawn off and renewed. When nitric acid is found, it is advisable to flush the cell with pure water.

TESTS FOR DETECTING IMPURITIES IN THE ELECTROLYTE.

1. **Test for Chlorine.**—Take a sample of electrolyte, acidulate with nitric acid, and add a few drops of silver nitrate solution; if a curdy white precipitate forms, which is soluble in ammonia, chlorine is present in some form.

2. **Test for Iron.**—Iron may appear in one of two forms, namely, ferrous or ferric salts. A small sample is taken and some concentrated hydrochloric acid added and then some potassium ferricyanide; if a heavy blue precipitate forms, ferrous iron is present; if in very minute quantities, a deep blue-green discoloration results.

3. **Test for Ferric Salts.**—To a sample of electrolyte add some hydrochloric acid and a few drops of ammonium thio-cyanate; if a blood-red solution or precipitate is the result, ferric iron salts are present.

4. **Test for Copper.** — To a sample of electrolyte an excess of ammonium hydrate is added; if a blue solution is the result, copper is present. It is advisable to check the test by taking another sample and adding some potassium hydrate to it; if a blue precipitate is formed which turns black upon boiling, it is additional proof of the presence of copper.

5. **Nitric Acid** being injurious even in very small quantities, it is advisable to make the following very sensitive test: Some diphenylamine in concentrated sulphuric acid is added to the sample; if a blue color is the result, nitrates or nitrites are present.

6. **Test for Mercury.**—Mercury may be present in two forms, mercurous or mercuric compounds. The *mercurous* compounds give a black precipitate with lime water, and a greenish precipitate with potassium iodide.

The *mercuric* compounds give a yellow precipitate with lime-water, and a red or scarlet precipitate with potassium iodide.

On account of possible difficulties the following is recommended:

1. Test every carboy of sulphuric acid before using.

2. Concentrated sulphuric acid should not be kept around, as it may be used by mistake, which would ruin the plates.

3. Only distilled water from carboys should be used and not from barrels, as it may be contaminated by the organic material.

4. Water from the city mains should never be used unless the amount of iron it contains is very small.

5. When testing with hydrometer for acid strength the battery should be fully charged and tests *always made at the same temperature*, because the specific gravity of the electrolyte falls with increase of temperature. The change due to temperature is as follows:

SPECIFIC GRAVITY OF DILUTE SULPHURIC ACID.

Temperatures.	30° F.	40° F.	50° F.	60° F.	70° F.	80° F.	90° F.	100° F.	110° F.
Sp. gr.	1.1593	1.1562	1.1531	1.1500	1.1469	1.1438	1.1407	1.1376	1.1345
"	1.2096	1.2064	1.2032	1.2000	1.1968	1.1936	1.1904	1.1872	1.1840
"	1.2620	1.2590	1.2530	1.2500	1.2470	1.2440	1.2410	1.2380	1.2350
"	1.3090	1.3060	1.3030	1.3000	1.2990	1.2940	1.2910	1.2880	1.2850
"	1.3620	1.3580	1.3540	1.3500	1.3460	1.3420	1.3380	1.3340	1.3300
"	1.4144	1.4076	1.4048	1.4000	1.3952	1.3904	1.3856	1.3808	1.3768

Putting the Battery out of Commission.—If, for any reason, the battery is to be but occasionally used, or the discharge is to be at a very low rate, a weekly freshening charge to full capacity at normal rate should be given. It frequently happens that a storage battery is put out of commission for a long period (for instance, in most summer or winter resorts the battery may be used for less than half of the year). In such cases the procedure is as follows: First the battery is given a complete charge at normal rate, then the electrolyte is siphoned off into carefully cleaned carboys (as it may be used again), and as each cell is emptied it is immediately refilled with pure water. When the acid has been drawn from all cells and replaced with water, the battery is discharged until the voltage falls to or below one volt per cell at normal current; when this point has been reached the water should be drawn off. In this condition the battery may stand without further attention until it is again put into service, which is accomplished in the same manner as when the battery was originally started. If during the discharge, when the water has replaced the electrolyte, the battery shows a tendency to get hot (100° F.) colder water should be added.

CHAPTER XXI.

APPLICATIONS OF STORAGE BATTERIES.

THE function of a storage battery is to receive electrical energy at one time or place, and to give it out at some other time or place.

The principal uses are the following:

1. To furnish portable electrical apparatus with energy.
2. To take up fluctuations, and thus steady the voltage and current.
3. To furnish energy during certain hours of the day or night, and thus enable the generating machinery to be stopped.
4. To aid the generating plant in carrying the maximum load (peak), which usually exists for only an hour or two.
5. To make the load on engines or other prime movers more uniform, by charging the battery when the load is light.
6. To transform from a higher to a lower potential by charging the cells in series, and discharging them in parallel, or *vice versa*.
7. To subdivide the voltage, and enable a multiple-wire system to be operated from a single generator.
8. To supply current from local centers or substations.
9. To supply current to electrically driven vehicles.*
10. As sources of current in telephone and telegraph systems.*
11. For car-lighting purposes.
12. As sources of constant potential and current in electrical laboratories.*

Portable Storage Batteries.—The storage battery is practically the only means of supply for portable electric lamps, or those not connected to a dynamo even when they are not portable. The primary battery is expensive and troublesome to operate; and is not commercially successful for electric lighting or power when more than one or two hundred watts is required. Nor is there any other

* Applications 9. 10, and 12 are not described, not being included in "Electric Lighting."

satisfactory primary source of electrical energy except a generator driven by mechanical power. It is therefore practically essential to adopt storage batteries wherever portable electric lamps, motors, etc., are used on any considerable scale.

The various manufacturers furnish portable forms of storage battery: for example, the Gould portable battery is arranged in a rubber jar, lead-lined box, or glazed earthenware jar, over which is placed a rubber gasket, and then a wooden cover clamped in place by U-shaped straps, passing around the containing vessel. For the escape of gas during charging, the cover has threaded holes which, when the battery is in use, are closed with hard-rubber stoppers. The usual number of cells in a case is from one to five, rated at 2 volts per cell.

A serious objection to portable storage batteries is their great weight. For example, a standard size weighing 100 lbs. yields 5 amperes at 10 volts, or 50 watts for 10 hours: just enough to feed a 16-C.P. lamp. The total discharge is 500 watt-hours or two-thirds of one H.P.-hour. The special forms of battery used in automobiles, including the Edison type, give about twice this output for the same weight. The weight of even the lighter types is almost prohibitive to portability except for automobiles, railway train lighting, and special purposes.

Portable batteries, for example, are used for feeding small motors, lamps, etc., for medical or dental purposes, in which cases their weight is not a serious difficulty in view of the importance of the work and the small amount of energy required. Small batteries are employed for theatrical lighting effects, being carried by the performers. Storage batteries are also used as source of power to drive small fan, kinetoscope, and other motors.

Storage Batteries for Preventing Fluctuations due to unsteadiness in the driving power or in the load, as with elevators, are often applied successfully. A dynamo driven by a gas-engine, for example, may vary periodically in speed because of the explosive action of the gas in the cylinder; and a battery connected in parallel with the dynamo will have the effect of steadying the voltage. A storage battery is often installed in connection with a small gas- or steam-engine lighting plant to enable the engine to be stopped for a considerable portion of the time, and thus save labor and attention, in which case the battery may also act to prevent fluctuations. A

windmill electric-lighting plant must have a battery or other means of storing energy, not only to eliminate fluctuations in speed which are continually occurring, but also to bridge over periods of calm weather.

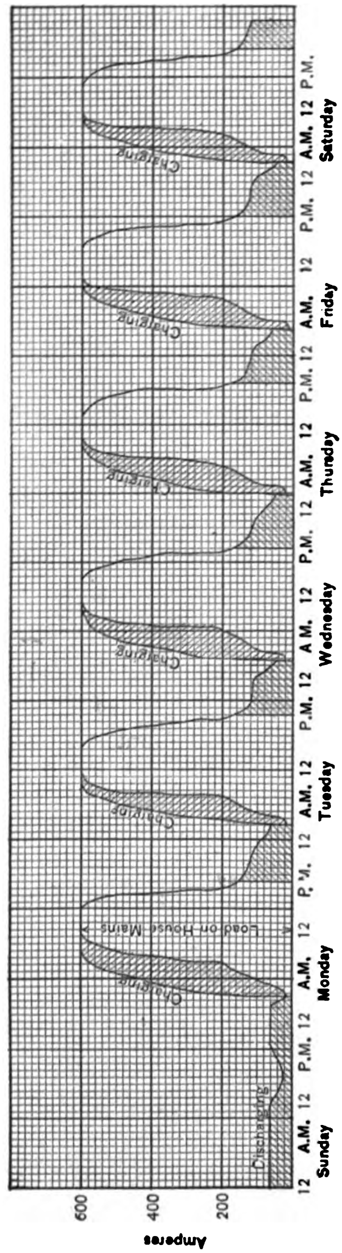

Fig. 175. Load Curve, Astor Court Building.

To Furnish Energy during Certain Portions of the Day or Night. — In almost every electric-lighting plant there are long periods during the day and late at night when the number of lamps lighted is so small that it may not pay to run the generating machinery. For example, Fig. 175 is a load diagram showing the weekly output of the electric plant of the Astor Building in New York City. The generating plant runs from 3 A.M. to 8 P.M. each day, the battery being charged from 3 A.M. to 11 A.M.; and when the generating plant is shut down at 8 P.M. the battery carries the entire load until 3 A.M., when the plant is started up again. Saturday nights the plant is shut down at eight o'clock, and the battery furnishes all the energy needed until three o'clock Monday morning. This enables the plant to be operated by two gangs or shifts; practically no labor being required for the remaining seven hours, as the battery carries the load, and the machinery is stopped entirely all day Sunday, giving a stretch of thirty-one hours once a week and seven hours each night for cleaning and repairs. In a hotel, resi-

dence, or on board a yacht it may be particularly desirable to stop the machinery and avoid the vibration and noise during the night.

Storage Batteries to Aid in Carrying the Maximum Load.— Assume in the case of the load diagram shown in Fig. 176 that the

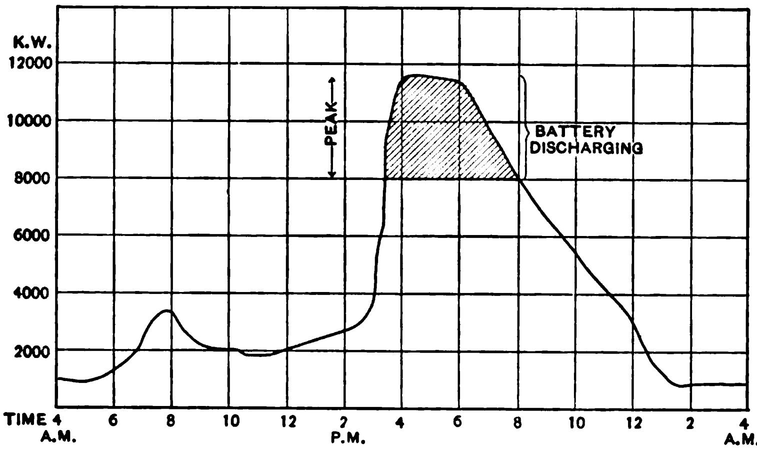

Fig. 176. Load Curve showing "Peak" of Load by a Storage Battery.

generating machinery is capable of supplying 8,000 kilowatts and that a storage battery is used to furnish the remaining 3,600 kilowatts at the time of maximum load, that is, the "peak" of the load diagram. This simply means that batteries are substituted for a certain portion of the machinery plant, and the question is whether or not the substitution is of advantage.

The first cost of a battery for a given rate of output depends simply upon the time of discharge. It usually has a normal period of discharge of about eight hours, at which rate its price to furnish a given number of watts would be 3 to 5 times as great as that of the equivalent boilers, engines, and dynamos combined; but if the time of discharge is reduced to about two or three hours, the costs are about equal, and with a still higher rate the cost of batteries would be less.

As a matter of fact, the storage battery secures other advantages, so that the total gain may be very important. For example, there is a reserve supply in case of accident and the load may be made more uniform, as will now be explained.

Storage Batteries to Maintain Uniform Load on Engines.— Steam-engines are very inefficient at light loads, and this fact often

causes serious losses in electric-lighting plants. Judicious selection of the number and sizes of the engines enable them to be worked in most cases at a considerable fraction of their full capacity nearly all of the time. Nevertheless the storage battery gives greater flexibility to the plant, and increases the economy of the engines by making their loads still more uniform, and nearer to full capacity while they are running. The engines can thus be made to run at approximately full load, the battery being charged when the external load is light, and the battery taking the peak of the load when it is heavy.

Storage Batteries Used as Transformers. — If the cells of a battery are arranged in series while being charged, and in parallel for discharging, a high voltage will be required for charging, and a low voltage will be given out. The amounts of energy measured in watt-hours are the same, less the loss of about 25 per cent which always occurs; the result is similar to that obtained by an alternating-current transformer or motor dynamo, but is less efficient. As an example of the converse arrangement the equipment at the Brooklyn Navy Yard may be mentioned. It consists of 250 small cells connected up in series-parallel of 5 sets of 50 cells each and charged on a 110-volt circuit. When discharged they are all connected in series and give about 500 volts, but with small current. This equipment is used to furnish 500 volts for insulation tests of cables, so that little or no current is required.

Storage Batteries Used for Subdividing Voltage.—The most important practical case is that in which a dynamo of 220 volts charges a battery of corresponding potential, a three-wire system being supplied from the battery, the neutral wire of which is connected to the middle point of the battery as represented in Fig. 177. This arrangement avoids the necessity of running two dynamos, and allows the battery to be placed in a substation near the district to be supplied, so that it is only necessary to run two conductors to that point instead of three.

The Hartford Electric Light Company was one of the first in this country to introduce the modern method of high-tension transmission, with low-tension three-wire distribution. The auxiliary storage battery used with this equipment consists of 130 chloride cells (65 on a side), each containing 31 negative and 30 positive plates, each $15\frac{1}{2} \times 31$ inches, placed in lead-lined tanks measuring

$58\frac{1}{4} \times 21\frac{1}{2} \times 43\frac{7}{8}$ inches. Fig. 178 is a diagram showing the general plan of the system. The power is transmitted 10.8 miles from

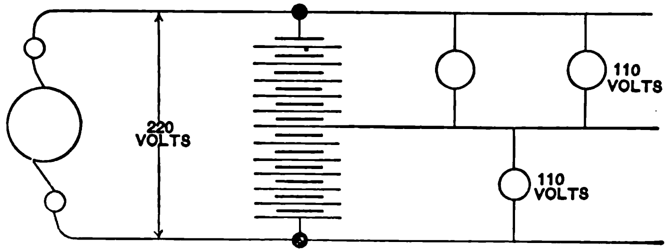

Fig. 177. Battery Used to Subdivide Voltage.

the Farmington River Power Station to the Pearl Street Station, in Hartford, by means of step-up transformers, a 10,000-volt trans-

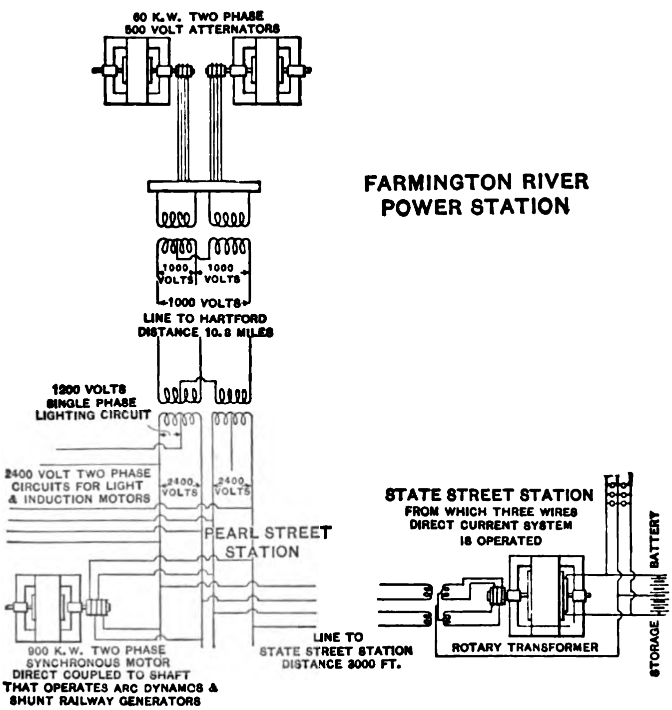

Fig. 178. Plan of the Farmington River-Hartford Distribution System.

mission line, and step-down transformers for distribution. From the Pearl Street Station to State Street, a distance of 3,000 feet, the current is transmitted at 2,400 volts, at which latter point, by means

of step-down transformers and rotary converter, the storage battery is charged and the current distributed over a low tension three-wire system.

Storage Battery for Substations.—The plan of installing battery plants at local centers, charged from the main station, enables one conductor to be saved in a three-wire system, as already stated. It also makes it possible to reduce the size of the conductors, because the current which flows over them can be kept practically constant, so that it is not necessary to have them large enough to carry the maximum, which may be several times the average value. The generating machinery has the same steady load as if the battery were located near it.

An excellent example of the storage battery substation is the Bowling Green Plant of the New York Edison Company. While acting as an auxiliary supply to the general system, the battery also takes care of the distribution of current to the extensive installation in the Bowling Green Building itself. The supply of current to charge the battery is taken from the Duane Street Station, about a mile distant, over four tie feeders equipped with controllable disconnective switch-boxes on the Bowker-Van Vleck plan. This enables them to be used as tie feeders by disconnecting them from the general system during the hours of light load, and as distributing feeders during the hours of maximum load, when they feed current into the system from each end. A considerable saving is thus effected in the investment because costly feeders are not required to supply the maximum load to a distant part of the system.

This installation of an auxiliary source of current supply in the lower district makes it possible to shut down the generators in the Duane Street Station during the hours of minimum load, the supply of energy to the district below 8th Street being derived from the battery plants at Bowling Green and 12th Street Stations, supplemented, if desired, by the supply from the 26th Street Station over the tie lines to the 12th Street Station, whence the current is distributed through boosters raising it to the required potential, over the tie feeders to the Duane Street Station switchboard. The battery- and operating-rooms of the Bowling Green Station are located in the sub-basement of the Bowling Green Office Building. Vitrified hollow tile for conducting the feeder cables are laid under

the battery-room floor, which consists of glazed white tile. Drains to carry off the water or acid run in the aisles between the cells and lead to small cesspools which discharge into a lead drain-pipe.

The battery comprises 150 Chloride cells, seventy-five in series on each side of the three-wire system. The cells consist of wooden tanks, 40¾ by 21½ by 30½ inches, treated with an acid-proof paint and lead-lined, each containing 14 positive and 15 negative plates 15½ inches wide by 31 inches high. Each tank is supported on

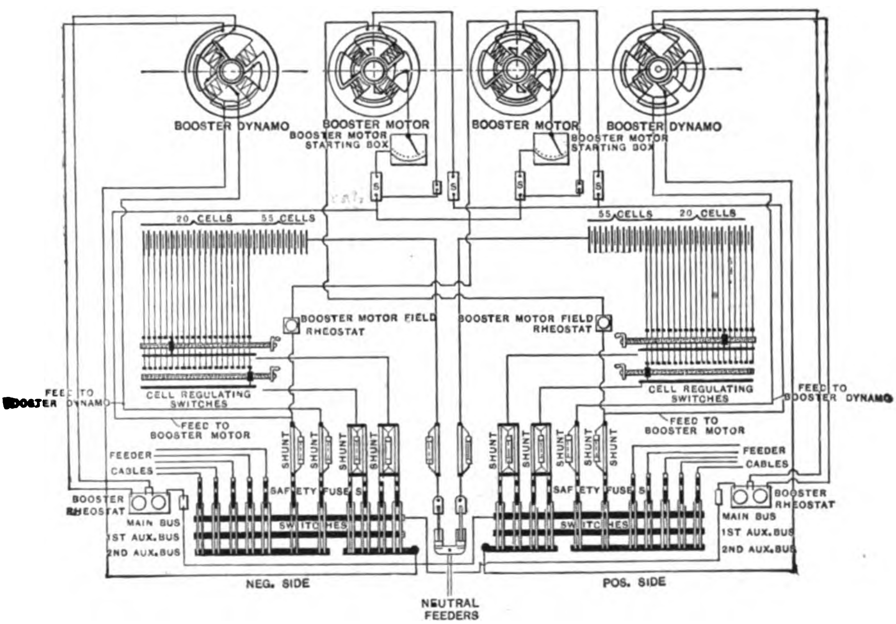

Fig. 179. Connections of the Bowling Green Storage Substation.

four petticoat porcelain insulators resting upon 6-inch glazed tiles. The plates are suspended in the tanks by shoulders resting upon heavy sheets of glass, which stand upon lead saddles in the bottoms of the tanks. The cells are connected by welding the plate terminals to lead bus bars, no mechanical connections being used.

Twenty of the end-cells on each side of the system are used for regulating, being separately connected to contact points on the regulating switches, which carry movable contacts operated by a screw. The potential is raised or lowered by cutting in or cut-

ting out the regulating cells. Two regulating switches are connected in multiple on the positive and two on the negative side to permit of discharge at two potentials, or to enable the battery to be charged and discharged simultaneously. The conductors between the two series of cells, and between the regulating cells and regulating switches, consist of copper bars 3 inches wide by ½ inch thick, supported on porcelain insulators resting in hangers. The connections of this equipment are shown in Fig. 179.

The capacities of the battery at various rates of discharge are: 2,000 amperes per side for 1 hour; 1,000 amperes per side for 3 hours; 400 amperes per side for 10 hours.

Provision has been made in the battery-room for the installation of a duplicate battery, to be placed over the present plant. The booster is used to raise the voltage from that of the system to that required for charging the battery. The booster can be used also to raise the voltage of discharge for feeding some distant point of the system at a higher potential than that normally required. It consists of one positive and one negative dynamo at each end of a common shaft driven by two motors. Each dynamo has a capacity of 1,200 amperes and a range of pressure up to 60 volts.

Storage Batteries Used for Two or More of the Above-named Purposes.—Each of the different uses has been considered separately to avoid confusion, but in most cases the storage battery is adopted in order to secure several advantages. By thus combining different applications the plant is rendered not only more economical, but also more flexible. For example, the battery may be utilized to help out the generating machinery at times of heavy load, or when the latter is partially or wholly disabled. It often happens that it is difficult to produce or maintain sufficient steam-pressure, owing to poor draft or other conditions, in which event a battery enables the boilers to be temporarily relieved of some or all of the drain upon them while the pressure is being raised to the proper point. It may also be necessary or desirable to shut down the machinery or a portion of it, temporarily, in order to make some repair or adjustment. It is possible to feed some of the circuits from the battery while others may be supplied at a higher or lower voltage by the machinery. In these and many other ways the storage battery may be a convenient adjunct to an electrical system. The fact that it is so radically different from the machinery

in its nature and action makes it unlikely that the entire plant will be crippled at one time, since the two sources of current are not exposed to the same dangers. An accident to the steam-piping, for instance, might shut down all the machinery, but probably it would not affect the battery; and, *vice versa*, an accident to the latter is not likely to extend to the former.

As an example of this application of the storage battery to several purposes, the following case may be cited:—

The power-house of the Woronoco Street Railway Company, in Westfield, Mass., contains two 75-kilowatt multipolar generators belted to two 120-H.P. high-speed, simple, non-condensing engines, steam being furnished by two 90-H.P. return-tubular boilers. The battery consists of 264 "Chloride" Type F–11 cells, in glass jars of Type F–13, permitting an increase of 20 per cent by the addition of one pair of plates in each cell, and is installed in a small brick extension to the power-house. The cells are located in one tier, each cell being supported on a sand-tray resting on four glass insulators. The foundation for each row of cells consists of two stringers of wood suitably braced and supported on brick piers. This battery was not installed as a voltage regulator, the feeders being so designed that the drop on the line is small.

Due to the battery the load on the machinery is reduced within the capacity of one unit, leaving the second one as a reserve in case of accident or unusually heavy load. Without the battery both machines would be needed nearly all of the time. The economy of operation, resulting from using one unit instead of two, is shown by the following station records:—

	Date, 1899.	Lbs. Coal.	Output, Kw.-hrs.	Lbs. Coal per Kw.-hr.
With battery..............	Oct. 25–27	16,250	3,032	5.36
Without battery...........	Oct. 28	6,250	981	6.37

This shows an increase in the coal consumption of 19 per cent on the day when the operation of the battery was discontinued. The plant is also noteworthy from the fact that the station attendance is reduced to one man per shift, the engineer doing his own firing. This arrangement could not have been continued under the conditions of increased load, had it not been for the improved regulation and reduction of coal handling, and the increased reli-

ability of operation secured by the battery. On several occasions the battery has been called upon to carry the entire load of the system for an hour or so, during a temporary shut-down of the rest of the plant, as well as early in the morning or late at night, when only one or two cars are running.

Storage Batteries for Train Illumination.—When cars are lighted by oil- or gas-lamps, these, owing to their size, and the heat produced by them, can be installed only in certain places, so that the distribution of light is not general, besides which, the heat and odor given off by the lamps are objectionable. The inflammable character of the illuminants involves great danger of explosion or fire in case of a train wreck. The absence of these disagreeable and dangerous features in electric lighting, is what has made its application so desirable in railway service. Several methods of electric illumination have been tried for this purpose. In one of the simplest a small dynamo, on the locomotive truck, or perched above the boiler, is driven by a small steam turbine. While this is an economical method, it has the objection that, when the locomotive is uncoupled, the cars must be illuminated by some other means.

For this reason, the storage-battery system of supply has been adopted. One of the most recent methods is the "Axle Light" System, in which the mechanism is suspended from the bottom of

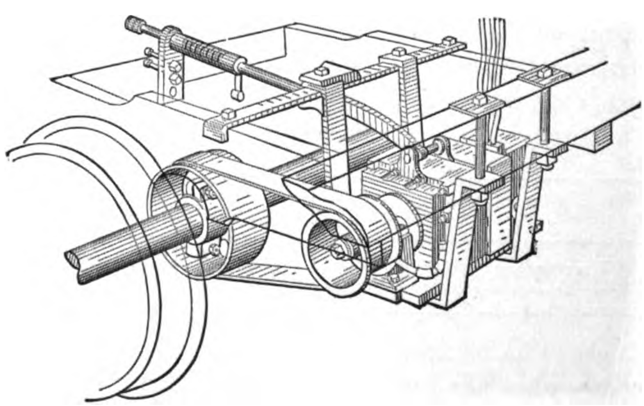

Fig. 180. Method of Suspension Axle Light System.

the car, and is completely incased, so as to be dust- and water-proof. It comprises a small dynamo driven from a pulley on the axle of the car by means of a friction coupling. The dynamo and driving

mechanism are shown in Fig. 180. The former generates from 32 to 40 volts, depending upon the speed of the train provided that it exceeds 15 miles per hour, the dynamo being then automatically connected to the battery and lamp circuit. An automatic device rectifies the direction of current, so that even when rotation is reversed, the battery is always charged in the proper direction. A variable resistance in series with the field-coils is automatically adjusted by a small motor, so that even at high speed the normal limit of voltage is not exceeded. The lamps are 16 C.P. at 30 volts, the filaments being short and heavy, so that they are not injured by vibration. After the storage battery has been charged, it acts in parallel with the dynamo and avoids fluctuations in voltage. When the car stops, the dynamo is automatically cut out and the full supply of current is furnished by the battery, which is large enough for a ten-hour supply at full load.

Connection and Regulation of Storage Batteries.—The complete control of a battery in an electric-lighting plant requires provision to be made for feeding the lamps, etc., from either the dynamo or battery separately, or from the two working in parallel; and it should be possible to charge the battery at the same time that lamps are being supplied. To accomplish these results requires three switches,—one to connect the battery to the dynamo, one to connect the lamps to the dynamo, and one to connect the lamps to the battery. In some plants the second switch is omitted, because the lamps are always fed by the battery alone, the latter being charged during the day, when no lamps are in use. However, it is desirable to have all three switches in every plant in order to be able to supply lamps and charge the battery at any time. In the battery circuit there should be an ammeter having a scale on both sides of zero, so that it shows whether the battery is being charged or discharged, as well as the value of the current. Another similar ammeter is required in the circuit between the dynamo and the battery, to show the direction and amount of current. A third ammeter is desirable in the lamp circuit, to show the total current supplied to the lamps; but it need only indicate on one side of zero, since the current there always flows in the same direction. A voltmeter is required with a three-way switch to connect it to the dynamo, battery, or lamps respectively.

An automatic overload switch must be inserted in the battery

circuit so as to open or introduce resistance into the circuit when the current becomes excessive. An automatic cut-out is required between the dynamo and the battery to open the circuit when the charging current falls below a certain value, and thus avoid any danger of the battery discharging through the dynamo, if from any cause the *E.M.F.* of the latter drops below that of the former. This completes the ordinary measuring and circuit-controlling

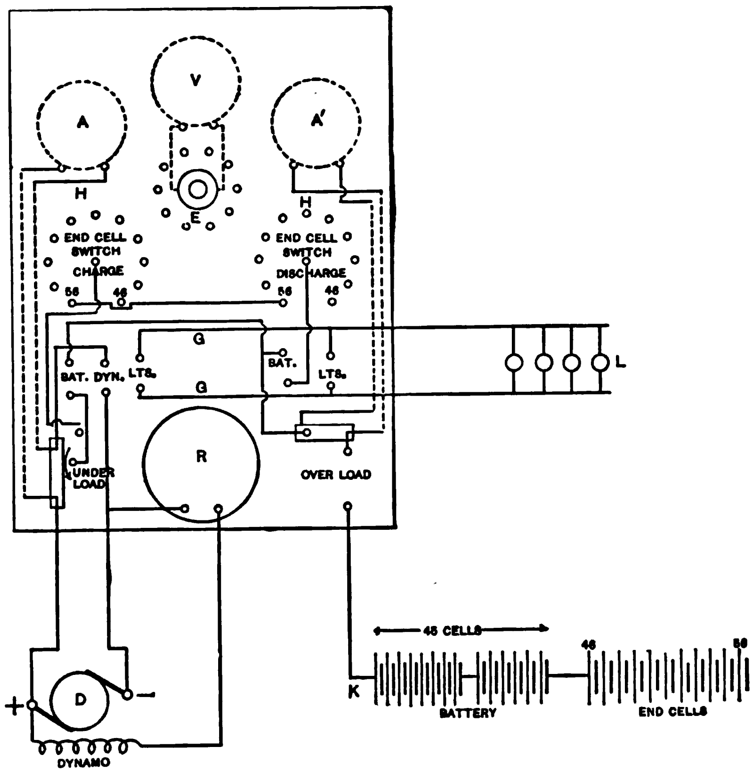

Fig. 181. Switchboard, Dynamo, and Battery Connections.

apparatus employed in connection with storage batteries. The arrangement is shown diagrammatically in Fig. 181, in which *A* and *A'* are the two ammeters, the third one being omitted in this case; *V* is the voltmeter; *E* the voltmeter switch to connect to the dynamo, battery, or lamps as desired; *G* the bus bars; *L*, lamps; *D*, dynamo; *R*, rheostat in field-circuit of dynamo.

The regulating device consists of eleven end-cells, which are connected to corresponding contacts on the end-cell switches (Fig.

181). But as the drawing of these connections would complicate the figure, they have been omitted. Fig. 182 shows the switchboard with these devices mounted upon it.

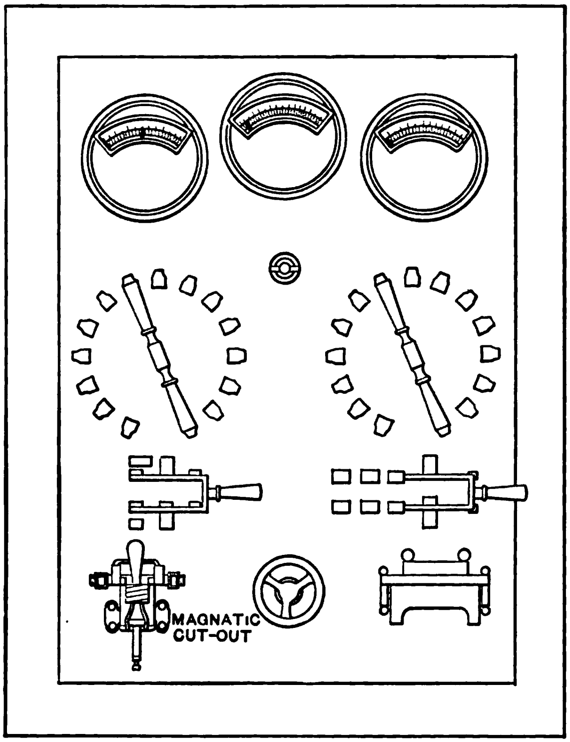

Fig. 182. Face of Switchboard.

The regulation of storage batteries is one of the most troublesome matters involved in their practical use. This arises from the fact that the voltage falls continually from the beginning to the end of discharge. To be sure, this decline is gradual; but its total value is large, being from about 2.2 to about 1.8 volts, which is a decrease of over 18 per cent.

In order to maintain a constant voltage, the usual plan is to have a number of extra cells, which are successively switched into circuit as the potential falls. These reserve cells and the switches which control them are represented in Fig. 181. The contact pieces of these switches must be made in such a way that they do not short-circuit the cells as they pass from one point to the next. This is accomplished by splitting the movable contact into two

parts, between which a certain amount of resistance is introduced, so that when the two parts happen to rest on two adjacent contact points, the resistance prevents the cell which is connected to these two points from being short-circuited, and also avoids breaking the circuit.

The number of extra cells depends upon the conditions; for 110-volt lamps, it would require 51 cells to obtain 112.2 volts when fully charged and giving 2.2 volts each, assuming the drop on the conductors at 2 per cent. When the battery becomes discharged, and its potential falls to 1.8 volts per element, 10 additional cells or 61 in all, would be needed. These would yield 111.8 volts, assuming the average potential of the reserve cells to be 2 volts, since they have not been discharged to the same extent as the original battery. If the drop on the conductors is 10 per cent of the lamp voltage, the potential at the battery will have to be $110+11=121$. This will necessitate 4 more elements, or a total of 65 when the 51 original cells are fully discharged to 1.8 volts, and the 14 extra cells give 2 volts each.

For a three-wire system the above figures should, of course, be doubled. This switching of extra cells into and out of the circuit obviously results in discharging them unequally, hence they require to be charged to a corresponding extent. This is accomplished by successively cutting the cells out of circuit as soon as they become fully charged, the last cell which was put into the circuit being fully charged in the shortest time, and so on. The amount of charge is determined by the methods already given. If the cells employed are not injured by overcharging, they may be left in circuit until the entire battery is fully charged. This saves the trouble of operating the switch; but it is wasteful of energy, since the full counter *E.M.F.* and resistance of the charged cells must be overcome, which requires about 2.5 volts per element. The switches might be operated automatically by a voltage regulator or by clockwork.

REGULATION OF GENERATOR IN CHARGING STORAGE BATTERIES.

The variation in *E.M.F.* which occurs in batteries renders it somewhat difficult to regulate the generators employed to charge them. A constant potential will give a decreasing rate of charge,

owing to the gradual rise in counter *E.M.F.* This is advantageous, in that it enables the cells to receive a larger charge, but the increase in their voltage is so great that it is practically necessary to regulate the charging potential. In practice it is customary to maintain the charging current approximately constant for considerable periods of time, otherwise it would be difficult to determine the quantity of energy put into the battery and its efficiency. When extra cells are used they facilitate the regulation of the generator, because they are gradually cut out as the *E.M.F.* rises.

If the lamps are supplied at the same time that the battery is being charged, some provision must be made for the fact that it is necessary for the voltage of the dynamo to be considerably higher than that required by the lamps. One plan is to have two separate switches connected to the reserve cells, as shown in Fig. 181, the charging current from the dynamo being led in through one, and the current for the lamps passing out through the other, so that the potential can be independently controlled in the two circuits. Another method is to insert counter *E.M.F.* cells (without active material) in the circuit between the dynamo and the lamps, in order to bring down the voltage of the former to suit the latter. The number of these cells is varied in accordance with the excess of the potential of the generator.

Simple resistance coils may be used in place of the counter *E.M.F.* cells to reduce the pressure; but the cells have the great advantage, that they have an effect practically independent of variations in current. All of these methods, however, involve waste of power, the value of which in watts is the product of the current in amperes, and the number of volts by which the potential is cut down. In small plants this loss is not serious, but in large plants or central stations it may become large.

Booster Methods of Regulation.—The best plan is to make use of a "booster"; in which case the main dynamos are run at the proper voltage to supply the lamps directly, and the additional pressure required to charge the battery is furnished by the booster. This is connected in series with the dynamos, being inserted in a circuit between the latter and the battery.

When a battery is placed at the end of a long feeder to compensate for line drop, and at light loads to act as a storage reservoir, it is not usual to equip this "floating battery" with any regulating

device. In such cases the battery is simply connected across the line, and the charge and discharge are determined by the feeder drop. For instance, when a small load is on the line, the drop is small, and the potential applied across the battery terminals is high enough to send a charging current into the battery. When the load on the line increases the drop naturally increases, the pressure at the end of the line falls, and if it falls below the battery voltage, the battery discharges in parallel with the generator, and carries a certain portion of the load. The "floating battery" has the advantage of simplicity, and acts immediately, as it does not have the time lag present in apparatus depending upon changes in magnetization. Usually the variations in voltage and fluctuations in load are too great for successful operation of a floating battery on any but an electric railway or power circuit, and a booster would be required if incandescent lamps be a part of the load.

The duty of a booster is to vary the voltage at the battery terminals with variation in load, causing charging or discharging of current as conditions may require. The booster is an auxiliary dynamo, the *E.M.F.* of which is used to raise or lower the voltage in the battery circuit. These machines are classified as series, shunt, compound, differential and constant current boosters.

The Shunt Booster is a shunt dynamo, driven by any source of power, having its armature circuit in series with the line from generator to battery. This form is used in plants, where the bat-

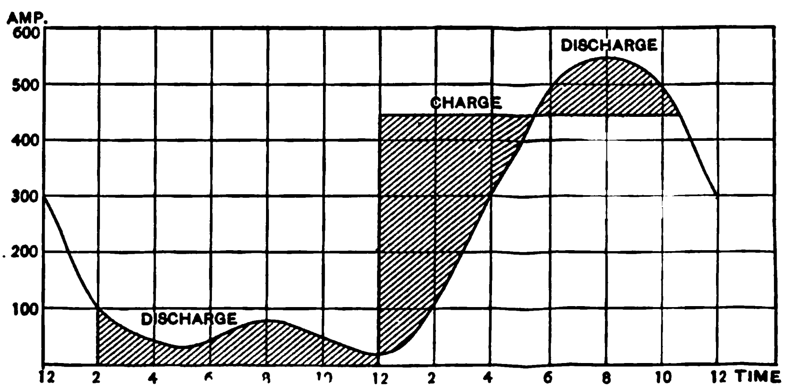

Fig. 183. Load Diagram of Case where Shunt Booster is Applicable.

tery is not designed to take up load fluctuations, but is in service only to carry the peak of the load, being charged during periods

of light load, and discharged in parallel with the generator. It acts to increase the voltage applied to the battery so that the charging current will flow into the latter. As a rule the battery used in conjunction with a shunt booster is made large enough to carry the entire load during the light load period. As the battery discharges and its voltage drops, the "end cells" (regulating cells)

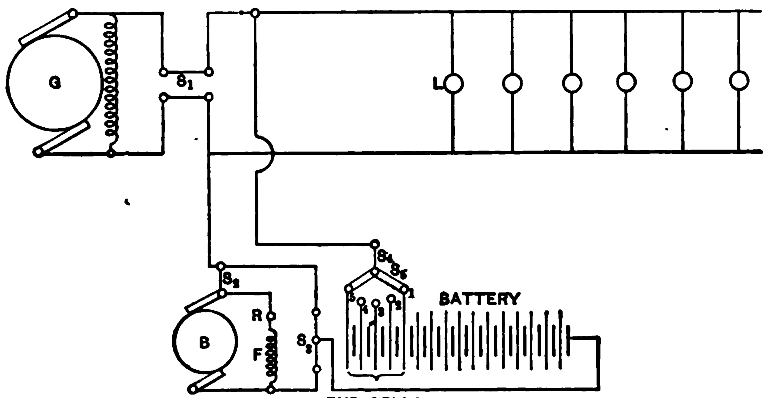

Fig. 184. Diagram of Shunt-Booster Connections.

are cut in and the proper voltage maintained. Fig. 183 is a load diagram to which this system is applicable, and Fig. 184 shows the connections. A rheostat is used to vary the booster voltage, so as to hasten the charging of the battery if desired. It is to be noted that the shunt booster is not applicable where there are sudden fluctuations that are great compared with the capacity of the generator, and that it is not automatic in changing from charge to discharge, the switching being performed by hand.

Series Booster.—The connections are like those of the shunt booster with the battery and booster in series across the line, but the field of the booster being in series with the battery circuits, its *E.M.F.* is zero when no current is flowing in or out of the battery. Should the voltage of the line rise, due to a decrease of load, and a charging current flow into the battery, the *E.M.F.* of the booster would increase, and thus tend to increase the rate of charge. The reverse occurs when the battery discharges, as an increase of load on the line increases the current through the series field of the booster, thus raising the voltage of discharge so that the battery carries a larger part of the load.

This booster acts to compound the battery on discharge, and tends to maintain a constant voltage on the line. It depends on the fact that the generator voltage falls when the load increases; hence it is used with a shunt generator or equivalent source of supply. This system is applicable to power but not to incandescent lighting purposes, being similar in operation to a "floating battery." It is not as extensively used as the compound and differential booster arrangements which give better regulation.

Compound Booster.—This system is used on railway and power circuits with great fluctuations in load, the battery acting to prevent excessive drop and to assist the generating machinery in carrying the load, relieving it from the strain of sudden rushes of current. The connections are indicated in Fig. 185, and the operation is as

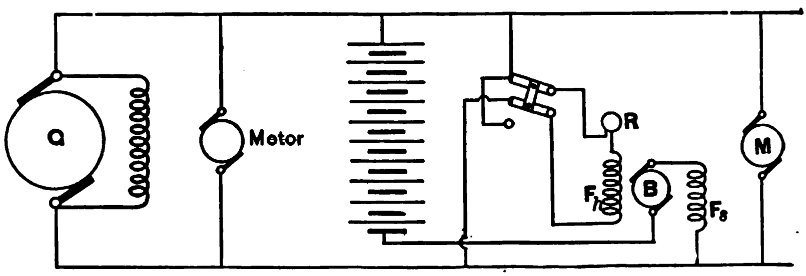

Fig. 185. Diagram of Compound-Booster Connections.

follows:—Under normal load conditions the shunt field *Fh* of the booster creates an *E.M.F.* in the same direction as the battery, tending to discharge it. Calling E_g the *E.M.F.* of the generator, E_a the booster *E.M.F.* and E_b the battery *E.M.F*, we have $E_g = E_a + E_b$ when no current is flowing into or out of the battery. In this case the generator carries the whole external load. If the load increases E_g decreases, so that $E_a + E_b$ is greater than E_g, and the battery begins to discharge. In discharging, the current passes through the series field *Fs* of the booster and produces a proportional *E.M.F.*, acting with the shunt field to raise E_a, thus increasing the battery discharge and shifting more of the load from the generator, until the system becomes balanced.

If the load on the external circuit be light, the generator voltage E_g rises and current flows into the battery. In this case the series field acts against the shunt field and decreases E_a, so that the generator voltage is greater than booster and battery voltage combined,

thus increasing the rate of charge of the battery, until the load causes the generator voltage to drop to normal and the system is again balanced. The battery and booster can be placed at the power house or where the greatest drop is likely to occur.

As this system, like the series booster, depends for its action upon the drop of voltage with increase of load, it is only applicable to shunt-wound generators.

Differential Boosters.—The differential booster system most commonly used is shown in Fig. 186. The compensating field-

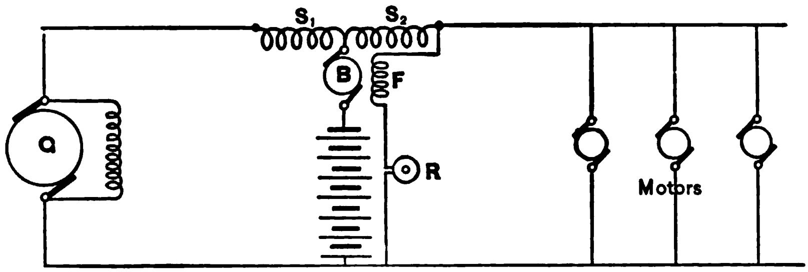

Fig. 186. Diagram of Differential Booster Connections.

coil S_1 opposes the shunt coil F and prevents the variation of the battery *E.M.F.* from disturbing the equilibrium of the system. If the battery *E.M.F.* be lower than normal it will not discharge rapidly enough to relieve the generator from overload fluctuations, unless the booster *E.M.F.* be increased, and the generator will therefore have to supply a current greater than normal. If a current greater than normal flows through S_1, the effect of the shunt coil F opposed by the series coil S_1 is decreased, and the series coil S_2 acting in the same direction as S_1 causes a higher booster *E.M.F.* tending to discharge the battery, and thus brings down the generator load to normal. Should the battery *E.M.F.* be above its normal value, the battery would discharge too rapidly and carry more than its share of the load; in this case $F-S_1$ is greater than it should be, and the booster *E.M.F.* causes the load to become evenly distributed between the battery and generator.

In operating this system the varying load must be beyond the booster equipment. The coils S_1 and S_2 may be temporarily short-circuited so that the battery may be charged more rapidly.

Constant-Current Booster.—In systems having short lines and small drop it is often desirable to have the voltage fall on sudden

application of an overload, so that the rush of excessive current is prevented. This rush of current occurs in buildings where elevator and other motors constitute a large part of the load, and to prevent it the constant-current booster is used.

In this system, represented in Fig. 187, the main current passes through the armature and series field of the booster, but does not

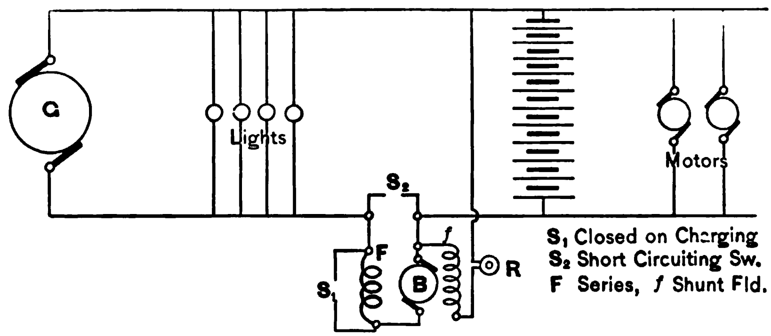

Fig. 187. Diagram of Constant-Current Booster Connections.

reverse. The voltage impressed on a fluctuating load of motors on the right is greater than that impressed on a non-fluctuating load of lamps on the left, by the amount of the booster voltage.

The shunt coil f of the booster creates an *E.M.F.* in the same direction as the generator *E.M.F.*, while the series coil F opposes it. Should a load come on the motor portion of the circuit, the generator sends a greater current through the series coil F, which reduces the booster *E.M.F.* in direct proportion and causes it to vary inversely as the motor load, thus tending to maintain an almost constant current delivery from the generator. The battery will furnish power to both the lights and motors, at periods of light load, without the generator, if the generator switch is opened and the booster short-circuited by closing switch S_2. The switch S_1 is closed in charging the battery, as the rate of charge can be controlled by varying the shunt field resistance R. This is often done when the battery has been carrying a heavy load for some time and the re-charging must be hurried.

The following are the most important books relating to storage batteries, the last three being recent and the others historical:

Recherches sur l'Électricité, by Gaston Planté, Paris, 1883.

The Storage of Electric Energy, a translation of the above by P. B. Elwell, London, 1887.

The Chemistry of Secondary Batteries, by Gladstone and Tribe, London, 1883.

Piles Électriques et Accumulateurs, by Émile Reynier, Paris, 1884.

The Voltaic Accumulator, a translation of the above by J. A. Berly, London, 1889.

Traité des Piles Électriques, by D. Tommasi, Paris, 1889

Secondary Batteries, by J. T. Niblett, London, 1892.

The Voltaic Cell, by Park Benjamin, New York, 1893.

Electric Light Installations, vol. i., Management of Accumulators, by Sir D. Salomons, Seventh Edition, London, 1894.

The Storage Battery, by A. Treadwell, Jr., N. Y. and Lond., 1898.

The Lead Storage Battery, by D. G. Fitzgerald, London, 1900.

Secondary Batteries, by E. J. Wade, N. Y. and Lond., 1902.

Storage Battery Engineering, by Lamar Lyndon, New York, 1903.

CHAPTER XXII.

SWITCHBOARDS, INCLUDING SWITCHES, FUSES, AND CIRCUIT-BREAKERS.

VARIOUS electrical conductors and apparatus, such as switches, measuring instruments, and other auxiliary devices, are required to connect and control the different dynamos and circuits in an electric-lighting plant. These might be considered to be mere details of the system, but they constitute a branch of the subject which is by no means insignificant.

Station Conductors. — Electrical conductors which connect the dynamos with the switchboard, and other conductors in the dynamo-room, may be arranged according to three different plans: —

1. They may run overhead as aërial lines.
2. They may be carried along the walls or ceiling.
3. They may be laid under the floor.

All three of these plans are commonly used, and the preference would depend upon circumstances.

1. *Overhead station conductors* possess the advantages of cheapness, shortness of path, and accessibility for inspection and repair; any short-circuit or ground could be instantly seen and removed, whereas it might occasion great uncertainty and delay in the case of conductors placed under the floor.

Overhead conductors in the dynamo-room may consist of rods of copper of circular or rectangular cross-section, and may be bare, provided the potential is not over 300 volts. In the case of high-tension conductors of 1,000 volts or more, they should be covered with insulating material, to prevent accidental contact with persons, or with wires or other conductors which might fall across or touch them. These conductors, whether insulated or bare, are supported by suitable rods or brackets. One of the simplest and neatest arrangements consists of an iron or brass

pipe, screwed into a flange or socket in the ceiling, and provided with a ring or strap at its lower end, which is lined with an insulating bushing of porcelain or hard rubber, through which the conductor passes.

2. *Conductors laid along the walls or ceiling* are similar in character and arrangement to those just described, and are often more easily supported; a simple porcelain insulator attached to the wall being usually sufficient, and applicable alike to high- or low-tension conductors. Low-potential wires may be laid in molding or interior conduits, similar to ordinary house-wiring; but in the station it is often desirable to have the main conductors visible and accessible, even though they may be somewhat unsightly, and this last objection can be largely avoided by neat arrangement.

3. *Conductors laid under the floor* have the advantage over either of the preceding plans that the wires are entirely out of the way; and this is an especially important matter in large plants, where an overhead traveling crane is almost a necessity for handling the dynamos and other machinery. Overhead conductors, or even those carried to the side walls, are decidedly in the way of a traveling crane, and interfere seriously with the great convenience which it affords in handling heavy machines or parts.

The placing of the wires under the floor also gives a clearer and neater appearance to the station. They have the disadvantage of inaccessibility already mentioned, and also the liability of becoming wet when the floor is washed. The first difficulty is overcome by providing a specially made trough or conduit in the floor, the cover of which is flush with the latter, and is made in convenient lengths to be easily taken up for examining or repairing the conductors. Wires under the floor should have a first-class moisture-proof insulating covering, so that they would not be short-circuited or grounded, even if submerged in water.

In case there is another story or space below the dynamo-room, the conductors can be run down through the floor, and carried along below on porcelain insulators, like the ceiling conductors already mentioned.

Since so much depends upon the perfect insulation and continuity of these conductors, the greatest care should be exercised in laying them, so that they are a sufficient distance apart at all points, and do not run too near any gas- or water-pipe, iron beam,

brick or stone walls, or other body which might ground or otherwise injure them. Where it is necessary for them to pass through a wall, partition, or floor, they should be insulated with a tube of porcelain or other suitable material.

All conductors, including those which connect the dynamos with the switchboard, as well as the 'bus bars or wires used for connecting the various switches, instruments, etc., should be of ample size to be free from overheating and excessive loss of voltage. It is not uncommon to find a drop in pressure of two per cent or more between the generators and the switchboard. This should be reduced to one, and preferably to one-half, per cent, because it interferes with the proper regulation of the apparatus, and adds to the less easily unavoided drop on the distributing conductors.

This subject belongs more properly under electrical distribution; but it may be stated as a general rule that these conductors should have a cross-section of at least one square inch per 1,000 amperes.

Switchboards. — In many of the early electric-lighting plants the switchboards were made entirely of wood; but so much trouble was caused by fire and short-circuits, that some non-combustible material is now considered almost essential. One of the best of these is marble; since it is a good insulator, is not hygroscopic, has a fine appearance, is not affected by any reasonable temperature, and can be obtained free from conducting veins, the last named being, in the case of slate switchboards, a source of great trouble. Slate has been extensively used for switchboards; and where it can be obtained free from the conducting veins just mentioned, it is an excellent material, since it is considerably stronger and tougher than marble. It is often "marbleized;" that is, treated in such a way as to fill the pores, and thus prevent the absorption of moisture, and at the same time make an imitation marble, which it is almost impossible to distinguish from the real.

Switchboards composed of glass plates or earthenware tiles have also been used with good results, white glazed tiles being particularly well suited to this purpose. Wood should not be used for a switchboard, except, possibly, where the switches, fuse-blocks, supports for wires, etc., are all of porcelain, or other incombustible substance, so that the wood, in the form of slats,

is merely a frame or backing to which these various devices are attached, all parts of the circuit being kept away from the wood, so that there is no danger of touching or burning it. Since marble, slate, tiles, or glass plates are not convenient to use in sizes larger than one or two feet square, it is necessary to make up large switchboards of many panels, which are held together by frames of iron, brass, or wood. The presence of a metal frame is, of course, objectionable, since it may cause short circuits; but it is customary to employ it, since it is a simple way to support the slabs of insulating material. Wooden frames have been substituted for metallic ones, the idea being that the switchboard itself is made of incombustible material, and the wooden framing merely holds it together.

The arrangement of instruments, switches, connections, etc., on a switchboard, should be conveniently and systematically carried out. The path of the current should be as short as possible, and preferably always in one direction; that is to say, it may pass from right to left, or from top to bottom, or *vice versa*, the wires being brought in on one side, and carried out on the other. The crossing of wires or connections is to be avoided as far as possible.

Wires, and all parts carrying current, should be placed far enough apart at all points to prevent accidental contact, or the jumping across of the current where the difference of potential is great. Wires and current-carrying parts must also be kept at a sufficient distance from conducting bodies, such as screwheads, metal brackets, gas-pipes, etc., to avoid accidental grounds or short circuits. Instruments and switches should be accessible for observation and operation; but, at the same time, parts carrying high-voltage currents must, if possible, be placed out of reach of accidental contact by persons, or else protected by an insulating shield.

There are three important classes of switchboards used in electric lighting:—

1. Low-potential incandescent lighting at about 110 or 220 volts.
2. Series arc lighting at 2,000 to 7,500 volts.
3. Alternating-current switchboards for 1,000 to 2,500 volts.

There are also many forms of high-tension switchboards used in connection with the long-distance transmission of electrical energy. Even in such cases, however, the pressure does not ordinarily exceed 12,000 to 15,000 volts, any higher pressure existing on the line being stepped-up and stepped-down by means of stationary transformers at the transmitting and receiving stations. It is a common practice in large cities to transmit three-phase electrical energy, at about 6,600 volts, from central generating stations to various substations, at which it is stepped-down in voltage and in many cases converted into direct current for distribution to the consumers. This important method is described in Chapter X, Vol. II. Examples of the different classes of switch-boards are given at the end of this chapter.

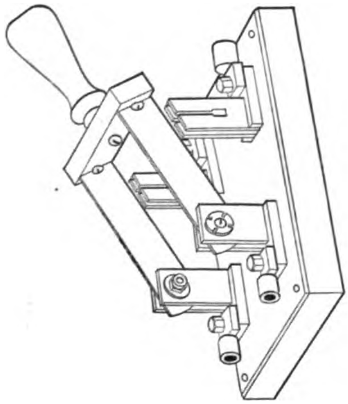

Fig. 188. Knife Switch.

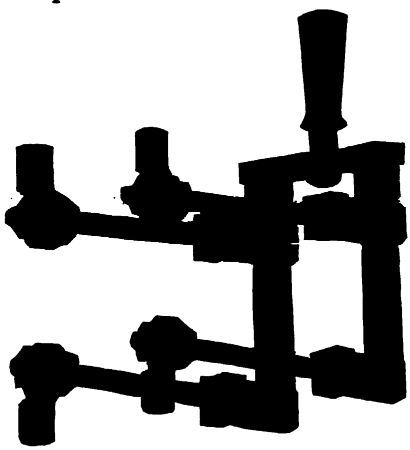

Fig. 189. Knife Switch.

Switches are devices for closing and opening the various circuits or branches. The *base* of a switch is made of slate, marble, or other fireproof material. In good practice, wood is no longer allowable for switch-bases. If, however, in an emergency it must be used, as, for example, when a marble switch-base has become cracked, it should be protected by a sheet of mica or

asbestus, to prevent charring of the wood. The base of a switch requires to be very strong in order not to break, crack, or bend, on account of the mechanical strains and the heating effect of arcs, both of which are quite severe in the case of large switches.

The contact surfaces of switches should be ample, the minimum area being .01 square inch per ampere; and in the case of arc-light or other high-voltage circuits where the current is usually small, the contact surface should be .02 to .05 square inch per ampere. The surfaces should have a *sliding contact;* a simple normal pressure between two surfaces being entirely unsatisfactory for the purpose, as the least dirt or oxidation would prevent good contact. In this country some of the well-known forms of "knife" switches are almost universally employed to control large currents, that is, those exceeding 10 or 20 amperes; but in Europe, switches are often used in which the contact is made by the ends of a number of strips of copper bent into semicircular form. This form of switch insures even better contact than the knife switch; but the objection to it is that the ends of the sep arate strips of copper dig into the contact surfaces and roughen them.

In the knife switch the blade enters between two copper springs or clips, which are pressed together, the blade often being made somewhat loose in order to adjust itself; in fact, perfect alignment and fit of the blade and the clips are somewhat difficult to accomplish, and is the chief trouble with this form of switch. Hence, to insure a good contact, particularly if the blade cannot adjust itself, the springs should be made flexible either by building them up of several thicknesses of metal, or by slitting them into a number of separate fingers. The contact pieces should be shaped so that they open along their entire length at the same time, otherwise the arc formed would concentrate at the last point or corner of contact, and thus burn or melt it away. Indeed, the arc produced by opening a circuit carrying a heavy current is one of the most difficult matters to control in practical electrical engineering; but ordinarily in electric lighting, circuits are not opened while a heavy current is flowing. In case of accident, however, it might be necessary to do this; and a switch should be capable of opening the circuit with full current a reasonable number of times without serious injury.

But if a circuit has to be opened very frequently, some of the forms of circuit-breaker, that are described at the end of this chapter, should be adopted.

In "quick-break" switches the contact-pieces are snapped apart by spring action, the object being to make the time during which the arc exists as short as possible. These are useful in many cases; but the most recent practice, particularly in large plants, is to employ circuit-breakers for interrupting currents of any considerable volume, either automatically or by hand. Simple knife switches are also provided; but their function is to close, rather than to open, circuits, and to make connections that are not likely to be broken while large currents are flowing.

All parts of a switch which carry current should have a cross-section of at least one square inch per thousand amperes for copper, and two or three times as much for brass. It is not uncommon to find switches in which brass pieces used to convey current become highly heated at full load. This, of course, is extremely objectionable, and probably arises from the mistake of making the brass conductors of the size that would be right for copper, whereas the former only has about one-third the conductivity. As far as possible, copper should be used for the current-carrying parts of switches and other portions of the circuit; and if brass is adopted because it is easier to work, or presents a more ornamental appearance, its lower conductivity must always be taken into account. In designing switches, the current should not be allowed to pass through springs which act mechanically, that is, those which are not mere contact springs; since the heat of the current is almost certain to "kill," or take the elasticity out of them. To avoid this, one or both ends of the spring may be insulated. The current should not be allowed to pass through any pivot, bearing, or fulcrum, as the contact is uncertain, and the current is likely to melt the parts together and prevent the movement of the switch. In small switches this rule is often violated, but in good practice the blade or arm itself should extend from one contact point to the other. The screws for holding the conductors should be large enough to stand being firmly tightened; iron screws with square or hectagonal heads are preferable to brass or slotted screws in the case of conductors of any considerable size. The effective length of the screws ought to be at

least twice their diameter to avoid stripping the thread; in short, considerable strength is required to hold the conductors firmly in place. Some device should be provided to hold the switch open and prevent accidental closing. This can usually be accomplished by simply placing the switch so that the arm hangs downward by gravity when it is open. The stupid mistake is often made of reversing this arrangement, so that the handle tends to fall and close the switch; which danger should be avoided, even if the switch is provided with a catch to hold it open. The handle of any switch, even for low-tension currents, must always be perfectly insulated. Special forms of switches for arc, alternating, and other circuits will be described under Electrical Distribution in Volume II.

Safety Fuses. — Almost all electrical circuits, except those for constant-current arc-lighting, are protected from abnormal increase of current by safety fuses. These consist of wires or strips of metal introduced into the circuit, and so designed in cross-section and resistance that they will melt and open the circuit in case of excessive current, before the rest of the circuit becomes unduly heated. These devices are extremely simple, and would seem to be very satisfactory for the purpose; nevertheless, much uncertainty exists in regard to the theory and practice of safety fuses.

The requirements for an effective safety fuse may be stated as follows: —

1. They should melt with a definite current.
2. They should not change in this respect by the effect of time, heating, or other action of the current, or in fact under any reasonable conditions.
3. They should act promptly.
4. They should give a firm and lasting contact with the terminals to which they are attached.

The ordinary practice is to manufacture spools or coils of wire, composed of some easily fusible alloy; or, for larger currents, flat strips of fusible metal provided with copper terminals are used. The idea is that each size of fuse will carry a certain normal current, but will melt and open the circuit with a certain excess of current, which is usually put at 25 per cent or $33\frac{1}{3}$ per cent increase. But, as a matter of fact, the fusing point is consider-

ably modified by many conditions, such as temperature of the surrounding air, position of the fuse, whether it be open or enclosed, vertical or horizontal, and whether it be on the floor, wall, or ceiling. The length of the fuse has also a great effect, the heat being rapidly absorbed from the ends of a short fuse by the blocks to which it is connected; and, furthermore, the size of these pieces would vary the amount of heat which they are capable of taking up.

It is evident, therefore, that the exact conditions under which a given fuse is to be used should be specified, in order to secure uniform results. In fact, fuse blocks or boxes should be standardized, in which cases they ought to be sufficiently reliable in their action, since the physical principles upon which they depend are simple and definite. Their construction is also so very simple and cheap that it would seem to be a mistake to give them up for more complicated devices, except in certain cases. The objection is often urged against fuses that they have a certain capacity for heat which allows the current to rise considerably above the normal point if it increases very suddenly. This is actually an advantage, because the conductors and apparatus which the fuse protects have a still greater heat capacity; consequently a momentary excess of current which does not melt the fuse cannot cause any injury in the rest of the circuit. This avoids the interruption of the supply and the renewal of the fuse every time there happens to be a rush of current for an instant.

A paper and discussion on "The Rating and Behavior of Fuse Wires," by Professor W. M. Stine and others, contains valuable information upon this subject.*

A report by Mr. W. McDevitt to the Philadelphia Board of Fire Underwriters on "The Gross Untrustworthiness of Fuse Metals and Appliances as a Means of Protection for Electric Circuits — The Remedy," † gives the results of many tests on fuses. It is a question, however, whether the difficulties are not largely or entirely due to improper and variable conditions, that can be avoided as already pointed out.

Electromagnetic Circuit-Breakers, cut-outs, or limit-switches are used in place of fuses to protect electrical circuits from exces-

* *Trans. Amer. Inst. Elec. Eng.*, October, 1895.
† *Electrical Engineer* (N.Y.), Feb. 5, 1896.

sive current. These circuit-breakers comprise the switch part as well as a solenoid in the main circuit, which acts upon a movable core. When the current exceeds a certain value, the core is drawn in and a trigger is tripped, which allows the switch portion of the circuit-breaker to fly open under the action of a spring. In the General Electric circuit-breaker, the main contact is made by heavy copper jaws, but the last breaking of the contact is made between points which are under the influence of a magnetic field. This magnetic field blows out the heavy arc that would otherwise be established. On the I-T-E, the Westinghouse, and most other types of circuit-breaker, the breaking of the contact takes place between carbon points, which are not so readily destroyed by an arc as are copper contacts, and which are more cheaply renewed. The main contact through the circuit-breaker, in either type, is made between copper jaws of sufficient cross-section to carry the current without heating. These jaws open before the current is interrupted by the smaller contacts which take the final arc.

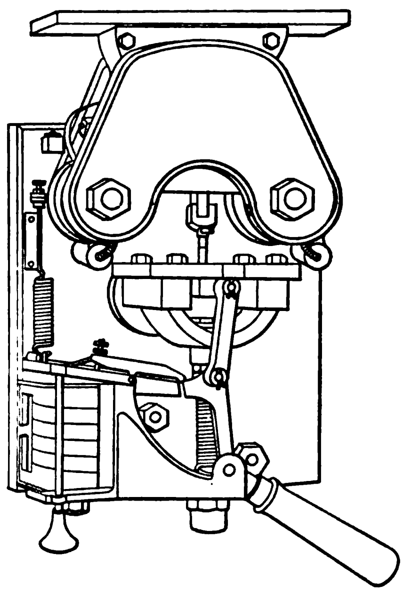

Fig. 190. G. E. Circuit-Breaker.

In Fig. 190 is represented a General Electric circuit-breaker with magnetic blow-out coils at the top, solenoid at the left, and handle for resetting the circuit-breaker at the bottom. The small handle for tripping the circuit-breaker when it is desired to open the circuit by hand is shown just under the solenoid.

An I-T-E circuit-breaker is shown in Fig. 191. This is of the type previously mentioned, in which the final break occurs between the carbon contacts at *A* and there is no magnetic blow-out.

Circuit-breakers possess the advantages over fuses that they can be instantly opened by hand if desired, they are readily closed and put in condition to act again, they can be set to open with a definite current, and do not injure the face of the board when opened under

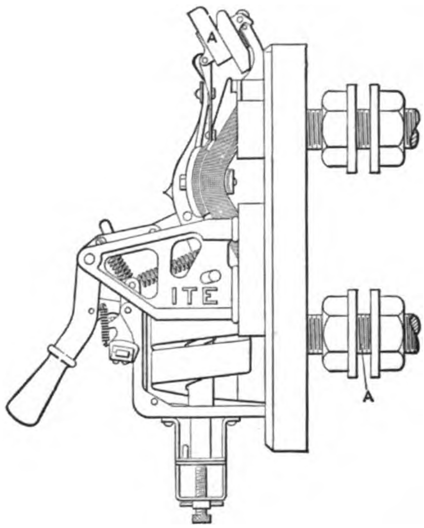

Fig. 191. I-T-E Circuit-Breaker.

load. In general, circuit-breakers are necessary for main circuits, or those frequently overloaded, especially in electric traction and power service. They should be used also for the principal circuits on electric-lighting switchboards.

Time-Limit Circuit-Breakers.—Where circuits are loaded with large induction or synchronous motors, or other devices liable to produce short circuits on the system when they get out of step or are suddenly connected, it is necessary to protect them with circuit-breakers, and in order to prevent their operation by momentary overloads it has been found advisable to introduce a time element on the circuit-breakers. This feature requires that the overload be maintained from three to five seconds before the circuit is opened. This factor may be introduced by either of two methods, namely, by a clock mechanism or by an adjusted dash-pot. The clockwork time-limit breaker devised by Mr. L. B. Stillwell, Fig. 192, is so arranged that the wheels are prevented from revolving by a pawl which may be lifted out of place by relay magnets, energized from the line by means of current transformers. The lifting of the pawl allows the clockwork to operate and close a low-tension relay

circuit, which trips the trigger of the breaker and thus opens the main circuit. The clock movement can be adjusted to close this second relay circuit in any desired time; and in case the mechanism is started by

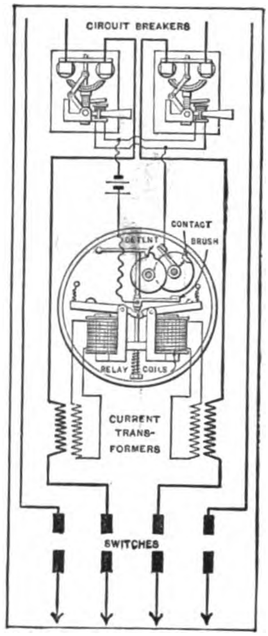

Fig. 192. Time-Limit Circuit-Breaker.

an overload, which is removed before the expiration of the time limit, the pawl drops and the movement returns to its original place.

In the case of the dash-pot circuit-breaker, the core of the solenoid is lifted against oil or air pressure, which can be so adjusted that the overload must be maintained for a definite period before the core can be lifted far enough to strike the release-trigger.

High-Tension Oil Switches.—Alternating-current generators for high voltages usually have oil switches to interrupt the main circuit, that is, switches in which the contact is made and broken under oil. These switches have been found very efficient in preventing the formation of a destructive arc upon opening circuits up to 30,000 volts. The larger oil switches are operated by electric motors or solenoids energized from secondary or relay circuits. The machine-type oil switch of the General Electric Company, Fig. 193, has the energy for operating it stored up in a spring which is wound up by a small electric motor. This motor runs every

time the switch is opened or closed, and winds up the spring enough to compensate for the amount it was unwound in operating the switch. Each "leg" of the circuit is broken under oil in a long tube, and these tubes are mounted in individual cells, sepa-

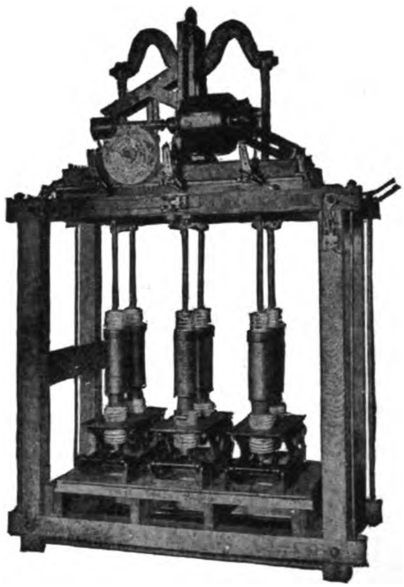

Fig. 193. High-Tension Oil Switch.

rated by masonry walls, so that there can be no flashing across from one to another.

Location of Switchboard.—In the design of buildings for central-station or isolated lighting plants, the switchboard should be located in an easily accessible place, and have plenty of space both in front and behind. In many instances the board can be placed to advantage on a gallery overlooking the generating machinery. Care should be taken to locate the switchboard with respect to the machinery and distributing feeders it is to control, so that the cost of copper may be kept down.

As extension should always be allowed for, the panels controlling the generators should be placed at one end of the board and the panels controlling the feeders should be placed at the other end.

For ordinary direct-current switchboards a space of about 3 feet should be left between the back of the board and the wall; for heavy work or high-tension systems a space of 6 to 8 feet would be advis-

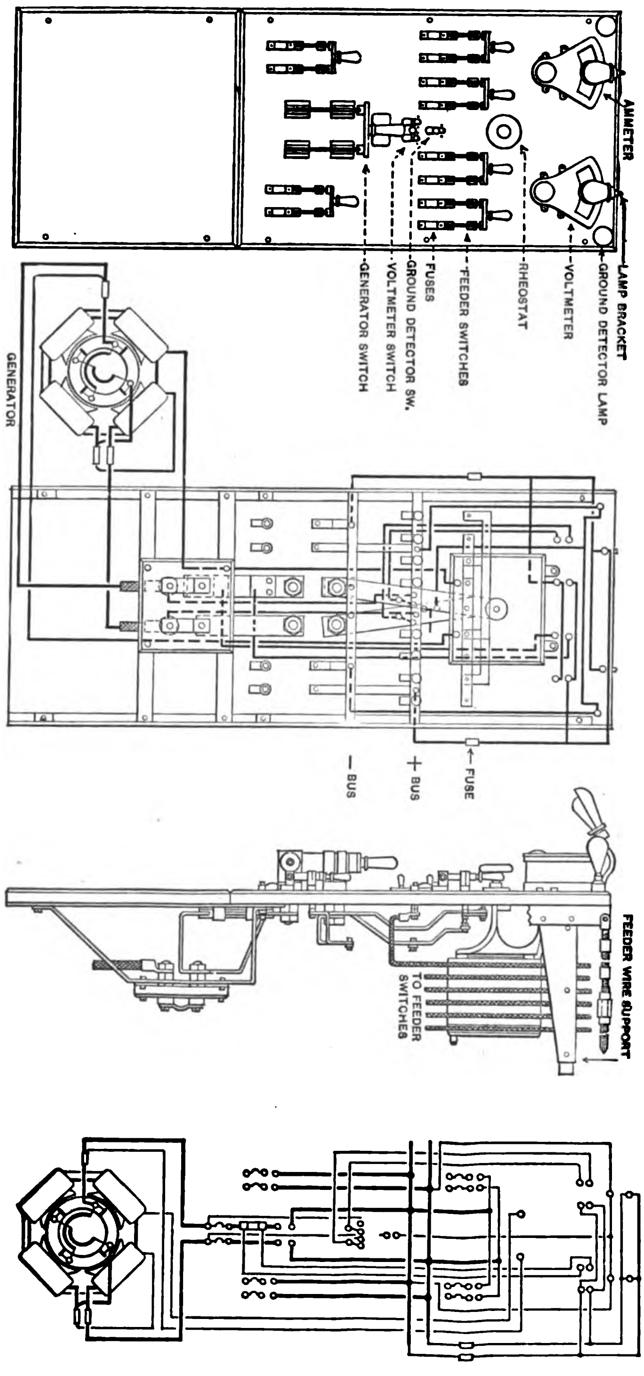

Fig. 194. Connections of a Typical Low-Tension Switchboard.

able. In all instances a space of not less than 10 inches should be left between the bottom of the board and the floor, and as much as 3 feet if possible between the top of the board and the ceiling, in order to lessen the danger of communicating fire to the floor or ceil-

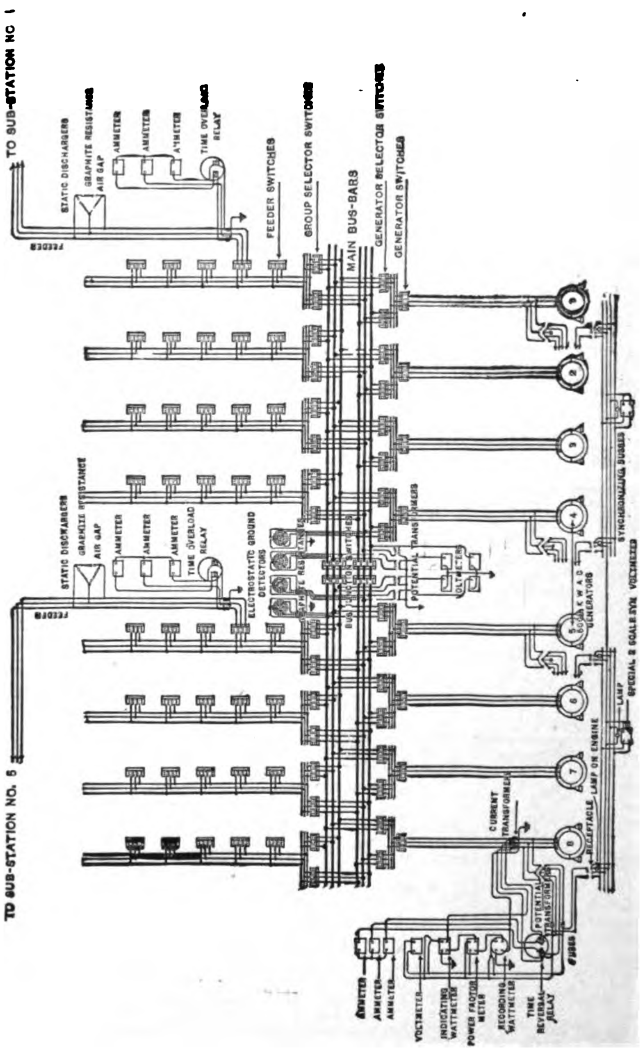

Fig. 195. Connections of a Typical High-Tension Switchboard.

ing, and to prevent the formation of a partially concealed space very likely to be used for the storage of rubbish, oily waste, etc. A typical low-tension isolated plant switchboard is shown in Fig. 194.

In systems working at 2,000 volts or more, it is excellent practice to remove all high-tension apparatus from the face of the board, the switches being placed in fire-proof compartments of brick or soapstone, and operated mechanically through bell-cranks and levers by means of handles on the face of the panel, or electrically

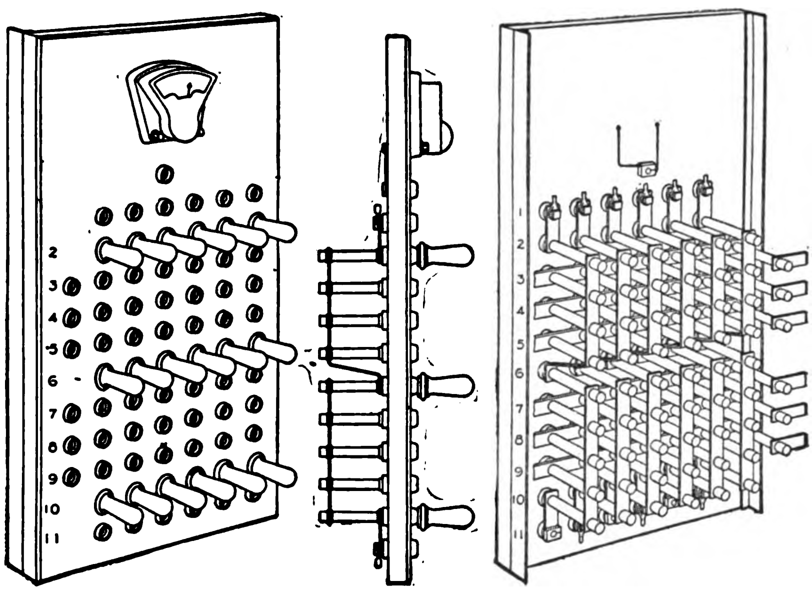

Fig. 196. Arc Circuit Switchboard.

by means of low-tension relays. The instruments are connected to the secondaries of potential or current transformers, which are conveniently located, and connected to the lines of the high-tension system. This construction naturally requires more space than the simple low-tension switchboard, but the danger of accidental contact is thereby greatly reduced. The main current-carrying apparatus may be placed directly back of the board, in the basement or upon a gallery, and inclosed in fire-proof compartments, or, if electrically controlled, the main apparatus may be located where desired. The general arrangement of instruments and connections of a modern high-tension switchboard is shown in Fig. 195.

Series arc switchboards differ from the other types mentioned, in that plugs are employed on them instead of knife switches; this

is possible because the currents are small, usually from 5 to 10 amperes. The function of the arc switchboard is to enable the rapid transfer of one or more arc-lamp circuits to and from any of a number of generators without opening the circuit. This transferring is sometimes accomplished by means of a pair of plugs connected by insulated flexible cables or by plugs without cables which bridge two contacts on the back of the board. The latter design is preferable, because the danger of contact with damaged cables is eliminated. The type of arc board shown in Fig. 196 is of the bridging type and is designed for three machines and three circuits.

CHAPTER XXIII.

ELECTRICAL MEASURING INSTRUMENTS.

THE subject of electrical measurements is one which should be treated in elementary and general works, or in those devoted to it. Being, however, extremely important and presenting a somewhat different aspect in each branch of electrical work, it is well to consider briefly the various classes of instruments and their applicability to electrical plants.

Classification.—The most important types of electrical measuring instruments may be subdivided as follows:

1. *Ordinary galvanometers.*—Coil acting upon permanent magnet.

2. *Electromagnetic devices.*—Coil or electromagnet acting upon soft iron.

3. *Electrodynamometers.*—Two coils acting upon each other.

4. *D'Arsonval instruments.*—Action between coil and magnetic field.

5. *Electrothermal devices.*—Heat generated by current produces expansion or other effect.

6. *Electrostatic instruments.*—Mutual action of two charged bodies.

7. *Electrochemical devices.*—Electrolytic effect of current.

8. *Miscellaneous instruments.*—Repulsion and other peculiar effects of alternating currents.

Galvanometers.—Until about 1888, practically the only instruments used to measure electric currents were simple galvanometers, consisting of a permanently magnetized needle, suspended or mounted so as to deflect by passing the current through a coil surrounding the needle. Ammeters and voltmeters had been brought out before that date, but were rarely employed because they were not very accurate. It was not until the Weston instruments were introduced during 1888 that results were obtained sufficiently reliable to warrant their general use for electrical measurements.

The galvanometer still remains the most sensitive means of detecting very feeble currents; but for almost all other uses galvanometers have been superseded by voltmeters and ammeters, and other more

practical forms of instrument. Its principal applications in electrical engineering are measuring the resistance of the insulation of circuits and apparatus, and locating faults in the same. Ordinarily insulation resistance has a value of many megohms, consequently it requires a very sensitive instrument to detect the minute current which would flow through such a high resistance. On the other hand, this delicacy is unnecessary, and in fact undesirable, if stronger currents are to be measured.

The D'Arsonval galvanometer differs from the preceding in the fact that the deflecting part consists of a coil of wire through which the current to be measured is passed, the coil being hung in a field produced by a permanent magnet. Compared with the other form this instrument possesses the great advantage that it is free from ordinary magnetic disturbances. For example, it is practically unaffected even by a dynamo at a distance of ten feet. A light pointer may be attached to the moving part of either style of galvanometer in order to measure the deflection; but for very feeble currents a very small mirror mounted on the moving part reflects a beam of light, thus obtaining the effect of a long pointer. In fact the deflection as read on the scale corresponds to twice the angular displacement. Formerly D'Arsonval galvanometers were far less sensitive than the magnetized needle type, but they have now been developed so that they have a high *figure of method*, that is, the number of megohms through which one volt will produce a deflection of one scale division.

These and other forms of testing apparatus should be put in a small room by themselves in a central station of any considerable size, being quite different in their functions from the ammeters, voltmeters, etc., which are placed on the switchboard for measuring the output of the plant.

Principles of Voltmeters and Ammeters. — In most cases there is no essential difference between these two kinds of instrument. For example, a galvanometer used to measure current is also capable of acting as a voltmeter, provided the resistance in its circuit remains constant, because the current which flows through it is directly proportional to the voltage. Similarly, any voltmeter which allows current to pass through it can be calibrated to indicate amperes as well as volts. Ordinarily, however, an ammeter is made with as low resistance as possible, being placed directly in the main circuit, because it is important that the loss of energy ($=I^2R$)

shall be a minimum. Conversely, the resistance of a voltmeter which is connected as a shunt to the generator or circuit ought to be as high as possible, in order that the current taken by it shall be insignificant. Nevertheless an ordinary ammeter may be calibrated as a millivoltmeter, because there is a certain voltage corresponding to each value of the current, that is, $V = IR$. In an analogous manner, almost any voltmeter (not electrostatic) can be converted into a milliammeter, because $I = \frac{V}{R}$.

Electromagnetic Ammeters depend upon the principle that a current tends to induce magnetism in, and exert force upon, a piece of iron.

A great many different forms have been made according to the same general plan, one of the simplest and best known being the "pendulum ammeter" formerly used in many Edison plants. This consisted of a coil in the form of the arc of a circle, which drew into itself a similarly shaped iron core swinging on a pivot.

The advantages of these electromagnetic instruments are their simplicity and cheapness. Their disadvantages are the fact that they do not indicate definitely near the zero-point; and for direct currents the hysteresis of the iron core causes the reading for a given current to be lower when the latter is increasing than when it is decreasing. For these reasons, this type should not be used where a considerable range of measurement is required or for direct currents. When employed for alternating currents the iron core is laminated or made up of fine iron wire to prevent the circulation of eddy currents.

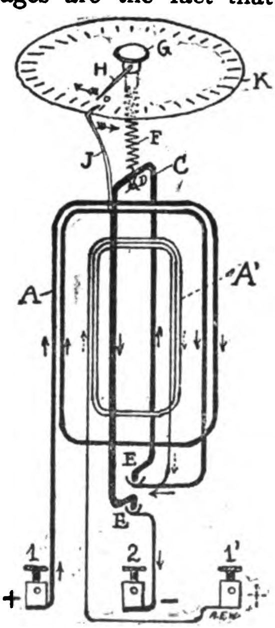

Fig. 197. Diagram of Siemens Electrodynamometer.

Electrodynamometers.—One of the oldest and simplest of these is the Siemens type, represented in Fig. 197, which comprises the fixed coil A and the movable coil C. The latter is large enough to surround the former, the two being placed so that their planes are perpendicular to each other. The movable coil is hung by a thread, or supported on a steel point, electrical connection being made to

it by mercury cups, *EE*. The current is sent through the two coils in series, which tends to turn the movable one into the same plane with the other. This force is balanced by a torsion spring, *F*, that is twisted in the opposite direction with a thumbscrew, *G*, through a certain angle, as indicated by a pointer, *H*, attached to the screw. The mutual force between the coils is proportional to the square of the current, and the force is in direct ratio with the angle of torsion; hence the current varies as the square root of that angle. The instrument is calibrated, or provided with a table which gives without calculation the number of amperes corresponding to the various angles. The extra coil, *A′*, consists of a greater number of turns, and is used to measure small currents, connection being made by the binding-post 1′ instead of 1.

The Kelvin (Thomson) ampere-balance, which depends upon the same principle, consists of two flat coils, *AA*, mounted like scale-pans upon the ends of a lever. These coils are acted upon by fixed coils, *CCCC*, placed above and below them, the force being balanced and measured by weights. The current passes through all of the coils in series, as indicated in Fig. 198.

Electrodynamometers are very accurate and constant, because there is no iron present to cause hysteresis; and they are applicable to either direct or alternating currents. They are, however, somewhat inconvenient to use, it being necessary with the forms described

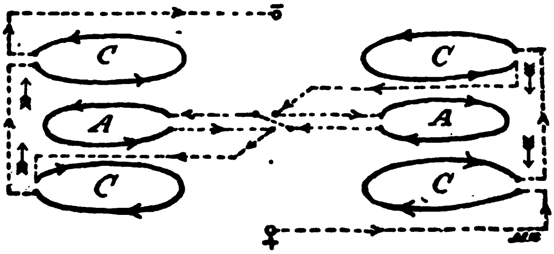

Fig. 198. Diagram of Kelvin Ampere-Balance.

to either twist a spring or move a weight, and the force, being proportional to the square of the current, is extremely feeble with small currents, and excessively strong with large ones; consequently the accurate range is quite limited. This objection does not apply when this principle is employed in wattmeters, which will be described later in the present chapter.

Weston Voltmeters and Ammeters resemble the D'Arsonval galvanometer in general principle. They embody, however, additional features and are constructed in a much more convenient and durable form; their perfection in design and workmanship being such that they are sufficiently accurate not only for practical use, but also for almost any laboratory measurement. The deflecting part consists of a coil of fine wire wound on a very light rectangular frame of aluminum or copper, mounted on jewelled centers, and carrying the pointer. This coil is situated between the poles of a

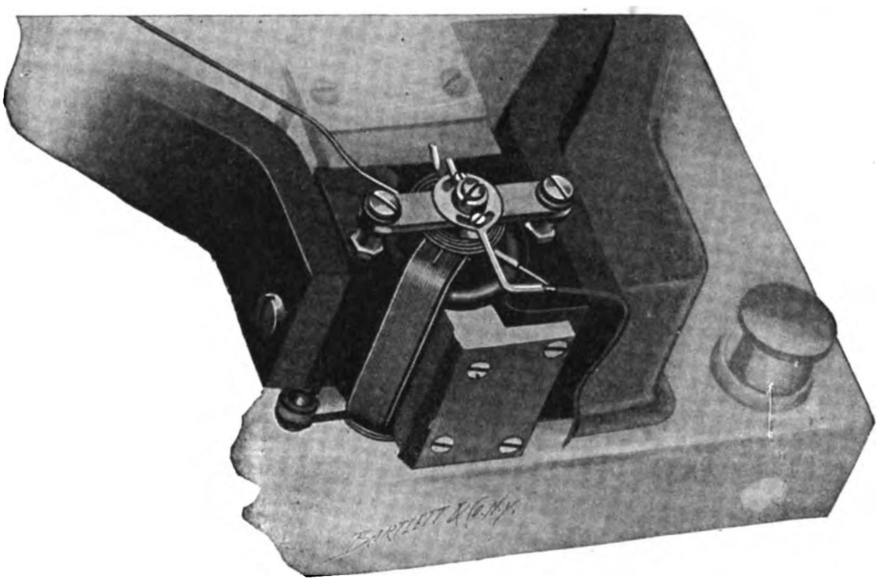

Fig. 199. Movement of Weston Instrument.

permanent magnet of horseshoe form. A fixed cylindrical core of soft iron is supported within the coil to reduce the reluctance of the air-gap. Two flat spiral springs are attached to the ends of the frame, and perform the double function of opposing the deflecting force and conveying the current to the moving coil. The ammeters and voltmeters are the same in external appearance and in construction, except that in the former the moving coil is in parallel with a shunt through which the main current passes, and in the latter it is in series with a certain resistance.

The merits of the Weston instruments are accuracy, portability, freedom from disturbance by stray magnetic lines, or by the effects of the ordinary changes of temperature, large range, uniform

scale-divisions over entire scale, accurate readings can be made quite close to the zero-point and very small consumption of energy. The above statements cover almost every desirable point in connection with electrical measuring instruments, except applicability to alternating as well as direct currents. For station use they are made in the form shown in Fig. 200, often provided with an illuminated dial consisting of a translucent scale lighted from behind by an incandescent lamp, the top of the latter being seen in the figure. These are placed on the switchboard, or at any other convenient point. A similar but smaller type is made for isolated plants, and a third style is the well-known portable instrument. All three of these forms are manufactured for various ranges, from those having scales graduated in millivolts, to those indicating 1,500 volts or more. This type not being capable of measuring alternating currents, another form is made for that purpose.

Fig. 200. Weston Voltmeter.

The construction and applications of the Weston instruments are very fully described in a series of articles by H. Maschke in the *Electrical World*, beginning March 26, 1892.

The Cardew Voltmeter was formerly used in large numbers, and is also interesting because its action depends upon the heating effect of the current. In it the pointer is caused to revolve by the expansion and contraction of a fine wire through which the current passes. This device can be used with either direct- or alternating-currents; but it is clumsy, the tube which contains the wire being nearly three feet long. It also consumes considerable energy, the current at full voltage being about one-third of an ampere, and involves a loss by no means insignificant if it continues twenty-four hours a day throughout the year, particularly when several are used in a plant.

Electrostatic Voltmeters.—In these instruments the mutual electrostatic attraction of two oppositely charged bodies is utilized to measure the difference of potential existing between them. The principle is identical with that of the electrometers used in labo-

ratory work. One of the simplest forms is Kelvin's vertical electrostatic voltmeter, consisting of two fixed metallic plates B, between which is pivoted a movable metallic plate, A, all three being parallel

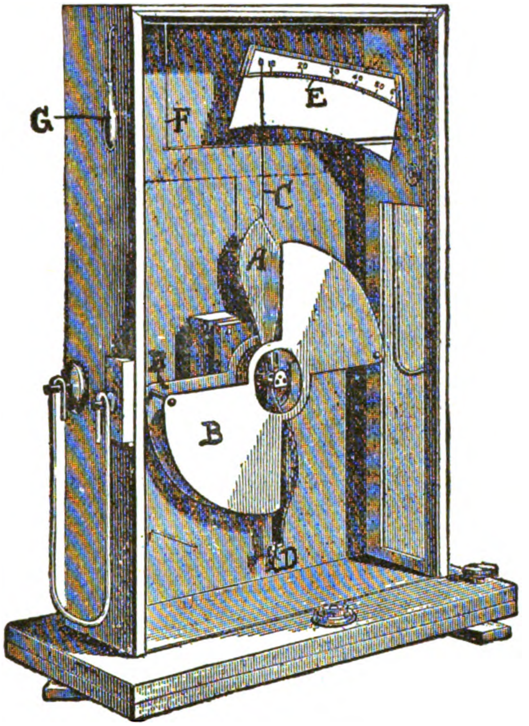

Fig. 201. Kelvin Vertical Electrostatic Voltmeter.

and vertical. The pair of fixed plates and the movable plate are respectively connected to the conductors between which the voltage is to be measured. This causes the plates to become oppositely charged; and the movable plate is deflected in its own plane against the force of a weight attached to its lower part, and the position of the pointer C is read on the scale E. The attraction is proportional to the square of the potenial difference; hence electrostatic instruments have a disadvantage similar to that explained in the case of electrodynameters. In fact, it is very difficult to obtain a practical electrostatic device which will measure pressures of less than about 50 volts. But in electric lighting the potentials used are very rarely less than 100 volts, and are often as high as 2,000 volts or more; consequently these instruments can be adapted to that purpose.

The advantages of electrostatic voltmeters are:—

1. They are applicable to either alternating or direct currents.

2. They are extremely simple in construction and action.

3. They are cheap.

4. Their accuracy does not depend upon any condition which is likely to change.

5. They consume no energy, since no current flows through them.

6. They are absolutely free from magnetic disturbance.

7. They can readily be made for measuring potentials up to 25,000 volts, or even more.

The last advantage is so decided that this type would seem best for very high potentials, and it possesses the six other advantages enumerated, even when employed for lower voltages. Up to the present time it has not been developed to the extent that its merits would seem to warrant. In practice, it is customary to measure high voltages by using a *potential transformer*, which reduces the pressure in the ratio of 10 : 1 or 100 : 1, so that an ordinary voltmeter can be used.

Electrochemical Instruments are not commonly used for practical measurements, almost the only example being the Edison electrolytic meter, described in Volume II. It was used in large numbers to measure the current supplied to the various customers, but has now been replaced by mechanical meters.

Special Alternating-Current Instruments.—Forms of ammeter and voltmeter have been devised in which effects peculiar to the alternating current are utilized. For example, the action of repulsion, discovered by Professor Elihu Thomson, may be applied to purposes of measurement. These have no great advantage over the ordinary electromagnetic and electrodynamic effects, and are not only limited to alternating currents, but also in most cases depend upon the frequency.

The Thomson Inclined-Coil Meter of the General Electric Co. is extensively used for alternating-current measurements. The working parts of the ammeter of this type are shown in Fig. 202. A coil A, through which flows the current to be measured, is mounted with its axis inclined as shown. A vertical spindle mounted in jewel bearings and controlled by a hair-spring passes through the coil; and to this spindle are fixed a pointer b and a vane of thin

sheet iron *a*. This vane of iron is mounted obliquely to the spindle. When the pointer is at the zero-point of the scale, the iron vane *a* lies nearly across the axis of the coil; and when a current passes through the coil, the vane tends to turn until it is parallel to the axis of the coil, thus turning the spindle and moving the attached pointer over the calibrated scale.

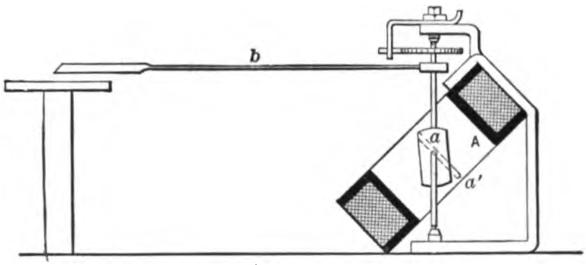

Fig. 202. Movement of Thompson Inclined-Coil Meter.

The inclined-coil voltmeter is identical with the ammeter, except that the former has fine wire in the fixed inclined coil, and in place of the iron vane, a coil of fine wire is employed, placed in series with the fixed coil, and with an auxiliary, non-inductive, high resistance.

Wattmeters.—If the Siemens electrodynamometer described on page 449 is modified by winding one of the coils with a great many turns of fine wire, connected to the circuit so that the current received by it shall be proportional to the voltage, the other coil being, as before, in the main circuit, and having the total current passing through it, the result is that the mutual action of the two coils depends upon both the pressure (volts) and current (amperes) of the circuit. In other words, the force exerted between them will be directly proportional to the product of the voltage and current, which is the number of watts.

For direct-current purposes a wattmeter is not so very important; since all that is necessary is to read the potential from the voltmeter and the current from the ammeter, and multiply the two numbers together to obtain the power in watts. But in alternating-current measurements the case is different; because there is a lag of the current wave with respect to the *E.M.F.* wave, if the circuit contains self-induction, as it almost always does. On the other hand, the effect of capacity is to produce a lead of the current; but

in either case the "apparent watts" obtained by multiplying the volts by the amperes, as indicated in different instruments, is not the real energy. This must be multiplied by the *power factor*, which is the cosine of the angle of lag, in order to find the "true watts." (Vol. II, p. 119.) It is difficult to determine this power factor; hence it is far more convenient to employ a wattmeter, which eliminates the error due to lag or lead so that the actual power may be read directly.

Recording Volt-, Ampere-, and Wattmeters.—These are employed in electrical generating plants to make a continuous record of the output in volts, amperes, or watts. For example, a pen or other marking-device is attached to the indicating part of a voltmeter, and a strip or circle of paper is slowly moved by clockwork so that a line is traced upon it showing the voltage at any time. These instruments require more positive action, and therefore more energy, than the ordinary visual meters that merely move a pointer

Ampere- and wattmeters are also made which integrate or sum up the total number of ampere-hours or watt-hours during a given period. These are chiefly used to measure the current supplied to each consumer, and they will be described under the head of Recording Meters in Volume II.

For further information on electrical measuring instruments, the reader is referred to:

Electrical Engineering Measuring Instruments, by G. Aspinall Parr.

American Meter Practice, L. C. Read.

Measuring Instruments for Switchboard Use, a paper read before the Institution of Electrical Engineers, London, by K. Edgcumbe, July, 1904.

CHAPTER XXIV.

LIGHTNING-ARRESTERS.

THE various devices employed to protect electrical apparatus from lightning or atmospheric electricity are commonly termed lightning-arresters. This name, however, is not very appropriate; since they do not in any sense stop the discharge, but merely act to *divert* it, and convey it harmlessly to the ground.

Lightning-arresters are required wherever an electrical circuit, or any portion of it, extends out-doors; but they are obviously unnecessary if the conductors are wholly in-doors, underground, or submarime. The liability of an aërial wire to receive discharges of atmospheric electricity depends upon its length, its height above the ground, and its location, that is, whether it runs over hills or mountains; and certain regions are far more subject to this trouble than others. In England, for instance, its occurrence is comparatively rare and insignificant, whereas in the Rocky Mountains it is a matter of serious and almost constant difficulty.

The troubles which are likely to be caused in an electrical plant by atmospheric electricity are:—

1. Puncturing or charring of the insulation of the electrical machines, instruments, or conductors.
2. Melting off of wires, or fusing together of contact points.
3. Danger to persons.
4. Liability of starting a fire.

The first or second of these accidents will often almost ruin an electrical machine or instrument, and involve considerable time and expense in repairing. The last two, although of less frequent occurrence, may be even more serious in their results.

In many cases where a circuit is partly overhead and partly underground or under water, there is danger that the former portions will receive atmospheric discharges, which, running down

into the subterranean or submarine cable, will break through its insulation in order to escape to the earth or water. This may necessitate very troublesome and costly repairs.

The Principles of Lightning-Arresters. — Since the introduction of the telegraph about fifty years ago, the ordinary form of lightning-arrester consisted of a conductor connected to the ground, and brought close to, but not in contact with, the circuit before it reached the instruments, as indicated in Fig. 203. The atmospheric electricity coming in from the line, being of high pressure, would jump across the air-gap, and pass directly to the ground, this path having less impedance than that through the coils of the instruments *I* and *I;* whereas the ordinary working *E.M.F.* is not high enough to traverse the gap. Points are usually provided on each side of the gap to facilitate the discharge across it. This device is fairly satisfactory if only weak battery currents are used. But in the case of electric light, or other circuits carrying strong currents, there arises a new difficulty. It is found that the dynamo current follows the discharge, and establishes a short circuit after having once been started by sparks passing across the gaps *A* and *A*, as shown in Fig. 204.

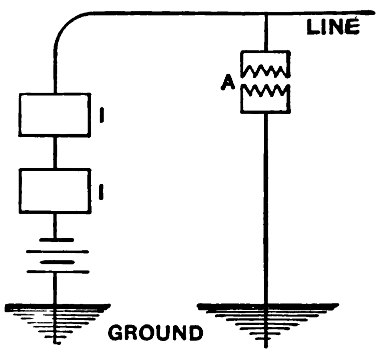

Fig. 203. Principle of Lightning-Arrester.

This would melt the dynamo fuses *F* and *F*, and interrupt the working current. With grounded circuits, an arc at one gap is sufficient to cause this trouble; but electric-lighting circuits, not being normally grounded, require arcs at both gaps to form a short circuit; but these are produced if the lightning comes in on both wires at once, which often occurs.

To obviate this difficulty, the spark-gaps were provided with automatic circuit-breaking attachments, which in their simplest form consisted of fuses in the discharge circuit, as indicated at *DD.* The fuses served to interrupt the short circuit without interfering with the working current; but these, having once melted, the plant was left unprotected from further discharges. Later the fuses were replaced by electromechanical devices, which should

not only stop the short circuit, but automatically readjust themselves for further operation.

The duty of the lightning-arrester, therefore, is to allow an indefinite number of static charges to pass freely to earth, and at the same time act as an effectual barrier to the flow of the current generated by the dynamo.

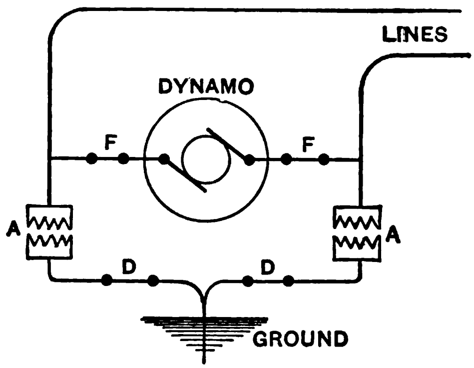

Fig. 204. Principle of Lightning-Arrester.

The numerous forms of lightning-arresters which have been brought out may be divided into the following classes, according to the means employed to interrupt the short circuit which tends to be established :—

1. Simple spark-gap, suitable only where working current is incapable of maintaining an arc across it.
2. Fuses in discharge circuit (as at *D*, Fig. 204).
3. Air-blast for blowing out arc.
4. Electromagnetic "blowing-out" devices.
5. Mechanical gap-lengthening devices.
6. Devices employing the so-called "non-arcing" metals.
7. Devices in which the arc is confined and smothered.
8. Arc dissipated by subdivision and distribution.
9. Arc prevented by introducing a considerable non-inductive resistance into the discharge circuit, which prevents the short-circuiting of the dynamo, but allows the high-tension charges to escape.
10. The presence of self-induction in the dynamo circuit opposes the passage of the discharge into the machine, hence coils are often inserted to add to the inductance of the machine.

Sometimes the arrester fails to interrupt the arc, and it becomes necessary to strike it out with a cloth or broom.

Comparatively few of these principles and forms of lightning-arrester have been applied successfully, and it will be sufficient to describe the most important of these.

The Thomson "Magnetic Blow-out" Lightning-Arrester. — Professor Elihu Thomson has ingeniously applied the action of a magnet upon a current to "blow out" the arc formed in lightning-arresters, switches, or similar devices.

It is well known that a conductor carrying a current tends to be moved or deflected in a magnetic field; and this is true whether the conductor be a wire or a conducting gas or vapor. Hence, if a lightning-arrester is provided with a magnet, placed so that the arc is formed in the field of the magnet, the arc will be repelled or "blown out," provided the direction of the magnetism and of the current is properly arranged.

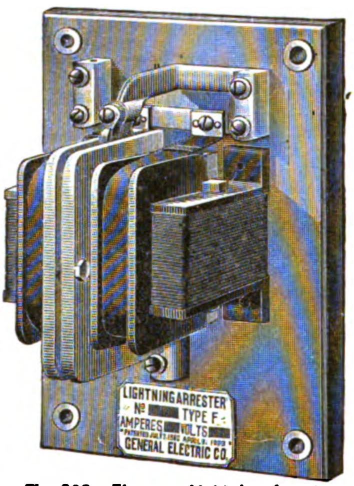

Fig. 205. Thomson Lightning-Arrester.

One form of this arrester for alternating-currents is shown in Fig. 205, in which the spark-gap is between the two large plates in the center, and is in the field of the electromagnet, which is wound with copper ribbon. The lower binding-post is connected to the earth, and the two upper ones to the dynamo and line respectively. When the arc is formed by the discharge jumping from the line to the ground connection across the gap, it is forced aside and broken by the action of the magnetic field upon it. The same principle is applied to various forms of lightning-arrester for arc and other circuits.

The Wurts "Non-arcing" Arrester.—A very simple form of lightning-arrester, devised by A. J. Wurts,* is manufactured by

* "Lightning-Arresters and the Discovery of Non arcing Metals," *Trans. Am. Inst. Elec. Eng.*, March 15, 1892; "Discriminating Lightning-Arresters and Recent Progress in Protection against Lightning," *Trans. Am. Inst. Elec. Eng.*, May 15, 1894.

the Westinghouse Electric Company. It consists of a number of cylinders (usually seven, each 1 inch in diameter and 3 inches long), placed side by side with air-gaps of $^1/_{64}$ inch between them. The cylinders are held in place by strips of marble or an equivalent insulating material, as represented in Fig. 206. The cylinders are knurled or checkered, and thus present hundreds of confronting points for the discharge. When a discharge occurs, it passes across between the cylinders from either or both line terminals to the ground. If, for example, both lines discharge simultaneously to the ground, then sparks will occur at all six gaps, which will make a conducting path for the dynamo current, and completely short-circuits the machine, as is apparent in Fig. 206. But the arcs are destroyed as soon as formed, and the short circuit does not last long enough to produce any bad effects.

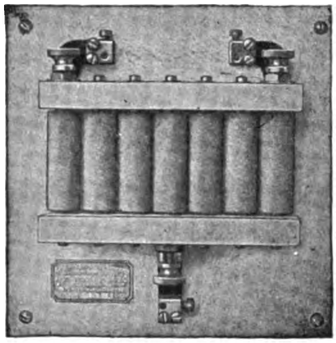

Fig. 206. Wurtz "Non-Arcing" Arrester.

Mr. Wurtz considers this action (see papers cited above) to be due to the fact that certain metals are non-arcing. These metals are the zinc group—zinc, cadmium, mercury, and magnesium; and the antimony group—antimony, bismuth, phosphorus, and arsenic, according to Mendelejeff's grouping. He does not explain why such is the case, but it may depend somewhat upon the volatility of these particular metals. The sudden evolution of considerable metallic vapor between the cylinders tends to blow out the arcs as well as to absorb the heat. This idea is borne out by the fact that Mr. Wurtz finds that the interruption of the arcs is more prompt and sure if the cylinders are very close together, i.e., $^1/_{64}$ inch, than if the gap be made greater. This indicates that confining the vapor tends to produce an explosive effect, which instantly extinguishes the arc, as it would in the case of a flame. It has also been suggested that the vapors of these metals may be poor conductors, perhaps due to the fact that at least some of them are monatomic, particularly at very high temperatures. Whatever may be the explanation, it has been found by experience that this form of lightning-arrester is effective in the case of alternating-current

lines, and that a large alternator may be repeatedly short-circuited by discharges passing across the gaps, without injury to the machine or to the arrester itself, the only effect being to very slowly burn away the cylinders at the gaps. Even this may be remedied by turning the cylinders so that they present new surfaces for the discharge. The material actually used for the cylinders is an alloy of zinc with just sufficient copper to enable it to be easily cast and worked.

On circuits of less than 1,250 volts the generator terminals are connected to the extreme cylinders and the ground line to the center

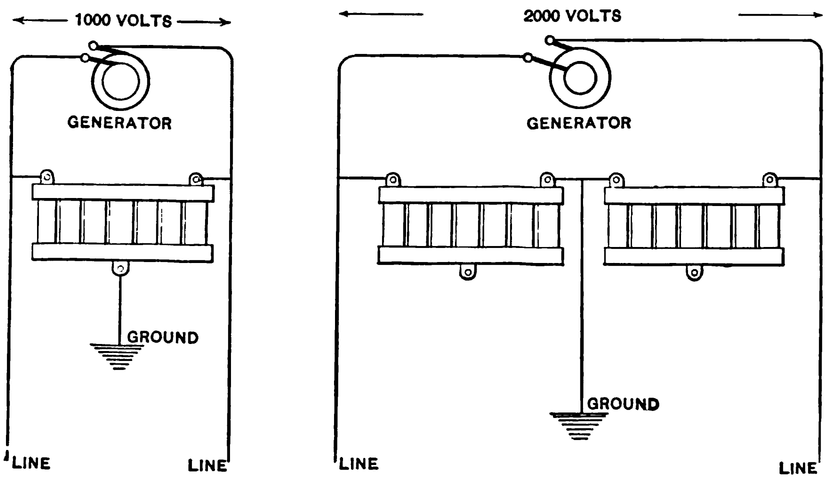

Fig. 207a. *Fig. 207b.*
Connections of Wurts Arrester on Systems of Less than 1,250 Volts and in Systems up to 2,500 Volts.

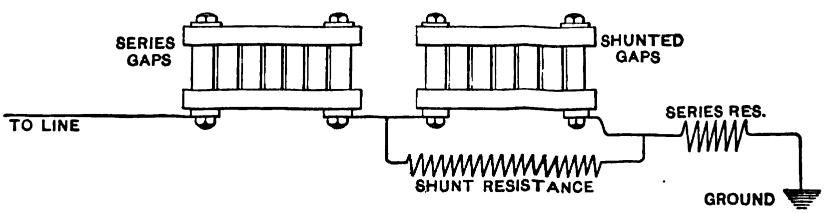

Fig. 208. Connections of Wurts Arrester on Systems of More than 2,500 Volts Pressure.

cylinder (Fig. 207*a*). The device is therefore double-pole; that is, one arrester is sufficient for both sides of the circuit. When the potential of the system is more than 1,250 and less than 2,500 volts, one complete seven-cylinder arrester is placed between each line wire and the ground (Fig. 207*b*). If the potential of the system

exceeds 2,500 volts, the arresters may be arranged as shown in Fig. 208. The operation of this equipment is as follows: To cause a discharge the potential at *A* rises until the series gaps are broken down. If the discharge is sufficiently heavy, it will then meet opposition in the shunt resistance "*R*" and will pass over the shunted gaps and to earth through the series resistance. The arc which tends to follow the discharge is then withdrawn from the shunted gaps by the shunt resistance and is suppressed by the series gaps aided by both resistances. The degree of protection secured is determined by the number of series gaps only, the shunted gaps being so proportioned that they are broken down by the potential thrown upon them when the series gaps discharge. The number of series gaps is just sufficient to withstand the normal voltage and allow a proper factor of safety assuming the severest condition, namely, that one line is grounded. The function of the shunted gaps is to provide a bypass for the lightning discharge which would otherwise meet opposition in the shunt resistance. The function of the shunt resistance is twofold: first, to withdraw the arc from the shunted gaps after the passage of the discharge; and second, to so reduce the volume of the arc that the series gaps, though too few in number to act successfully unaided, can, with this assistance, suppress the arc. The function of the small series resistance, which is made as non-inductive as possible, is to limit the initial flow of current tending to follow the discharge and thus to prevent burning of the arrester cylinders.

This type of arrester is employed for alternating-current circuits, and also for certain arc systems (Westinghouse, Brush, and Schuyler); but they are not applicable to direct currents of large volume, such, for example, as 110- and 220-volt incandescent lighting and 500-volt power circuits. With heavy direct currents the arc is too strong to be interrupted in this way, and some other form of arrester must be employed.

Another form of lightning-arrester invented by Mr. Wurtz, and manufactured by the Westinghouse Electric Company, operates upon the principle of smothering any arc which tends to be formed. It is shown in Fig. 209, and consists of two brass plates imbedded in a block of lignum vitæ, and separated a distance of half an inch. The space between has narrow grooves burned in it as indicated in the figure, and it is over or through these that the discharge passes.

This charred surface does not, however, act to any extent as a conductor for the dynamo current, since the resistance between the brass plates is over 50,000 ohms. If, now, the lignum-vitæ cap, shown on the left of the figure, be firmly screwed down over the charred grooves and brass plates, it will be impossible for an arc to form. The device allows static discharges to pass, but will prevent the flow of the large current which follows the discharge. This

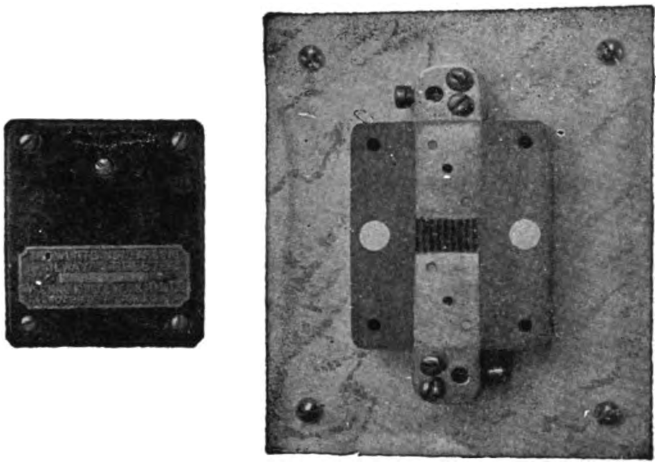

Fig. 209. Wurtz Direct-Current Lightning-Arrester.

arrester is especially intended for railway circuits (550-volt), but it is also applicable to other direct-current circuits up to 1,000 volts. It also operates satisfactorily on 1,000-volt alternating circuits from smooth-core armatures; but with toothed-core armatures it breaks down, and short-circuits after a few discharges. Its extreme simplicity is a strong point in its favor.

The Tank Lightning-arrester, shown in Fig. 210, is also a form used by the Westinghouse Electric Company for direct-current circuits. It consists of coils of heavy wire, with several discharge circuits leading from different points of the coils to carbon electrodes immersed in a tank of running water. The coils are connected in series with the apparatus to be protected, and between the latter and the line. The tank is thoroughly grounded, and so divided by partitions as to insure circulation of the water. The resistance of the discharge circuits may be changed by varying the depth of immersion of the electrodes.

When lightning tends to follow the line to the apparatus, the coils of the arrester interpose an inductive resistance to its passage, while the several discharge circuits of very small inductance offers comparatively easy paths to earth. The advantages of this device are—the discharge does not have to jump even the smallest air-gap; there is an opportunity for constant leakage of the static charge, which prevents the accumulation of a potential sufficiently high to break through the insulation of the generator or transformer, and at the time of discharge a short circuit of the apparatus is prevented by the resistance of the water.

The disadvantages of this arrester are that it allows a certain leakage of energy to occur through it all of the time, it is some-

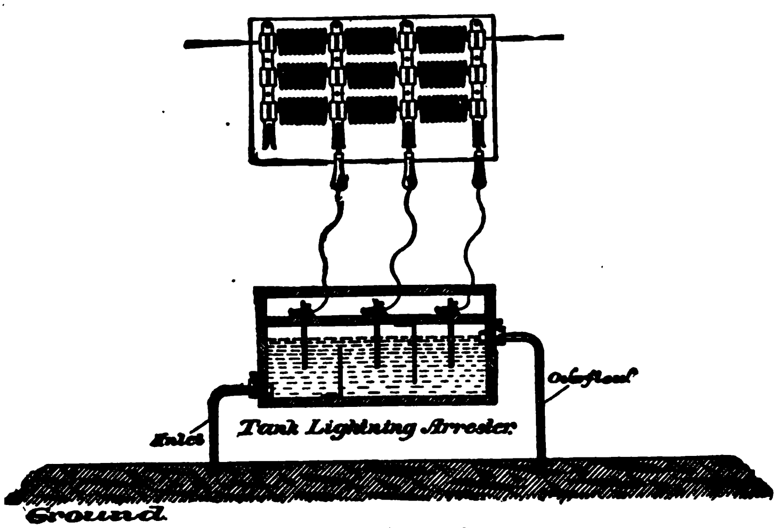

Fig. 210. Tank Lightning-Arrester.

what clumsy in form, and requires a stream of water to be kept running through it. These difficulties can, however, be reduced if the discharge circuits are disconnected by pulling out the plugs shown in the figure, when there is no danger of lightning discharges, during which time the flow of water may also be stopped.

This type is intended for electric-railway circuits (550-volt); but it might be applied with slight modifications to electric-lighting circuits, and it is interesting as being one of the few examples of lightning-arresters which steadily drain the static charge from

the line without allowing it to accumulate, as already pointed out. A very simple device of this kind consists of an ordinary plank, which is always kept wet by water dripping upon it. One end of this plank is connected to the line, and the other to the ground, so that any static charge by reason of its high potential will pass into the earth through the plank, but the resistance of the latter is great enough to prevent any serious leakage of the generator current.

The "S.K.C." Lightning-Arrester, manufactured by the Stanley Electric Manufacturing Co., of Pittsfield, Mass., consists of two nests of concentric cylinders with diverging ends held in their

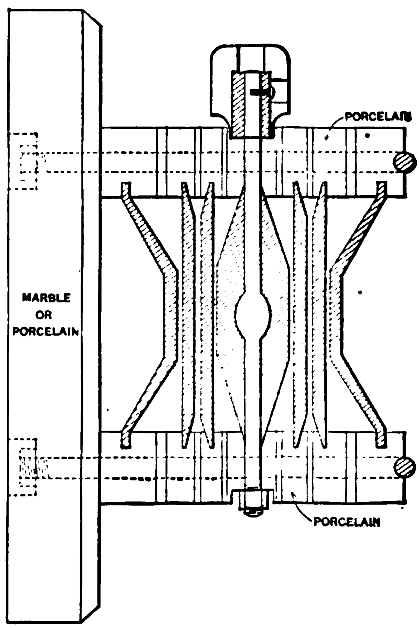

Fig. 211. "S.K.C." Lightning-Arrester.

positions by porcelain caps as shown in cross-section in Fig. 211. The innermost cylinder is connected to the line, and the outer one to the ground. The porcelain caps are provided with grooves so placed that all spark-gaps are $\frac{1}{16}$ inch wide. Between the grooves are a number of perforations to allow the free circulation of air between the cylinders. If, after a lightning discharge, the current from the generator follows the lightning, there is a rush of air

forced by the metallic vapor through the perforations and spaces between the cylinders, blowing the arc upwards between the flaring ends, where it is instantly ruptured.

According to the construction of this arrester there are three spark-gaps each $\frac{1}{16}$ inch wide in series between either line-wire and the ground. At ordinary commercial frequencies, five thousand volts or over are required to jump the series of gaps of the arrester, but at the higher frequencies of lightning discharges the sparking potential is reduced to less than one-half of this.

Barbed Wire Lightning-Arrester.—This consists simply of a barbed wire laid immediately over the line throughout its entire length, or where it is particularly exposed. This wire is connected to the ground at various points, and protects the line by taking up and carrying to earth discharges which the line would otherwise receive. This is essentially different from other methods of protection from lightning in which the static charge gets upon the line, but is made to escape from it before reaching the apparatus. This plan is used in the case of the Lauffen-Heilbron power transmission line, and has also been employed in this country. It would seem to be one of the most effective means of protection; but it has the disadvantages of requiring an extra wire to be laid, with the necessary supports, etc. Mr. Wurtz* cites a case at Staten Island, N. Y., where this plan was successful, but states that at Telluride, Col., it was a "total failure." But the troubles from atmospheric electricity are so very great in Colorado, that this case may be considered as exceptional; and it is probably a fact that a guard wire over the line, the former being grounded at frequent intervals, will protect the latter under the conditions which exist in most places.

Choke Coils for A. C. Circuits.—A lightning discharge being of an oscillatory character is very much affected by inductance and passes with difficulty through a coil of a few turns of wire. The frequency of the oscillations of a lightning discharge is far higher than that of commercial alternating currents, hence a coil can be readily constructed which will offer great reactance to the passage of a lightning discharge, and at the same time allow the generator currents to pass freely. These coils are placed in series with the main

* *Trans. Amer. Inst. Elec. Eng.*, vol. xi., p. 386

circuit between the generators and the ordinary lightning-arresters.

Line Dischargers or Static Drains.—The majority of arresters require a comparatively sudden rise of potential in order to act properly, while in many instances the accumulation of a static charge is gradual. To avoid this latter occurrence and remove even slight charges from the lines, an instrument similar to that illustrated in Fig. 212, called a "Line Discharger," is employed. This device con-

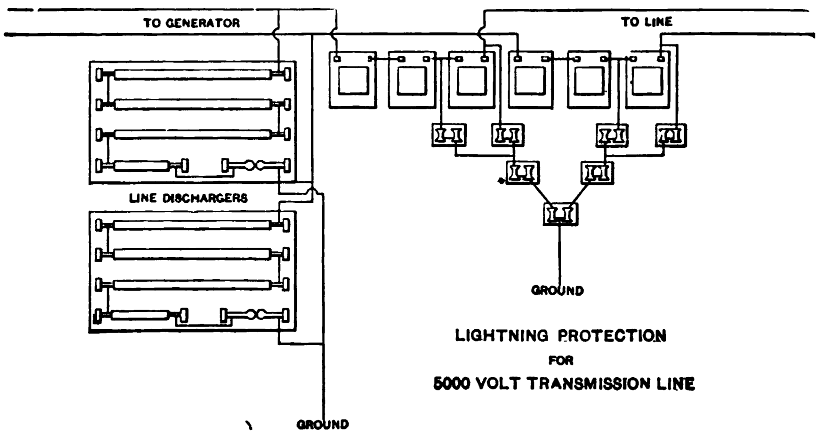

Fig. 212. Line Discharger.

sists of a minute air-gap in series with a set of tubes of insulating material filled with a powdered metallic oxide, thus offering a practically infinite resistance to the ordinary currents, yet allowing static charges to pass readily to earth. Such a line discharger is connected, as shown in Fig. 212, the number of tubes required depending upon the voltage used.

Location of Arresters.—Ordinarily lightning-arresters are placed on each overhead line or feeder after it enters the station, but before it reaches the switchboard or any apparatus. In the case of grounded circuits, one arrester is sufficient for each, as indicated in Fig. 203; but in the case of a metallic circuit both lines, and for three- or four-wire systems, each wire should be provided with arresters, as shown in Fig. 204. Long lines are not sufficiently protected, however, by the station-arresters, and it is wise to place them on the line at not very great intervals, and particularly at points which are much exposed, or where there are sharp turns in the circuit. They should also

be arranged to protect transformers or other apparatus wherever they may exist on the circuit. Mr. Wurts, in his paper and discussion on "Discriminating Lightning-Arresters," * strongly insists upon the importance of placing arresters at numerous points, and argues that in this way the failure of one arrester may be retrieved by the others. He even uses groups or "banks" of lightning-arresters, placed one after another on the circuit; and

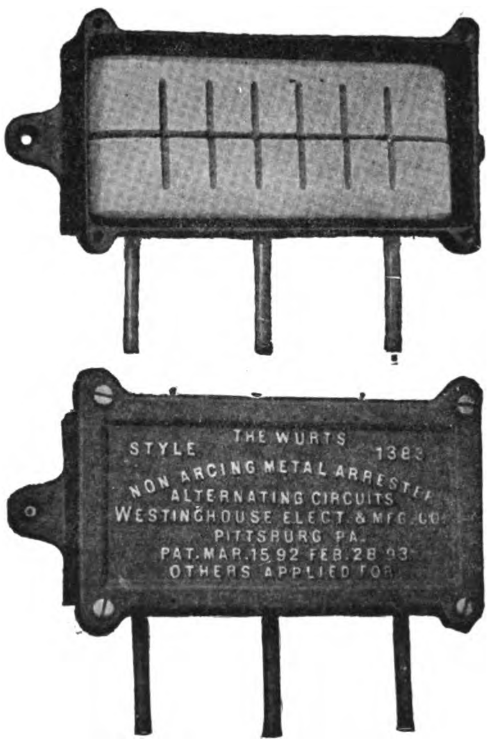

Fig. 218. Wurts Lightning-Arrester Arranged for Outdoor Use.

also recommends the use of different kinds of arrester in some cases, for the reason that one type may be better suited to a discharge of a certain character. He further points out that disruptive discharges form nodal or neutral points along the line, at which there is little or no tendency to discharge. Hence a single arrester may utterly fail to act. Whether these views be accepted wholly or not, it is certainly a wise precaution to have

* *Trans. Amer. Inst. Elec. Eng.*, May, 1894.

more than one arrester to depend upon, since they are not very costly, and at least are not likely to do any harm.

The so-called line lightning-arresters for outdoor use are made very compact, and inclosed in a waterproof box, as represented in Fig. 213. If possible, arresters should always be placed directly on the main circuit, or have the circuit itself brought to them, instead of merely connecting them by a branch wire.

Ground Connections. — It is of the utmost importance that lightning-arresters should have very good ground connections, and the conductor from the arrester to the earth should be as short and straight as possible. In the case of a central station, a hole five or six feet square should be dug, as nearly as possible under the arresters, and deep enough to reach permanently damp earth. The bottom of this hole is covered with one or two feet of crushed coke or charcoal (about pea-size), over which is laid a copper plate of 20 or 25 square feet area, and not less than $\frac{1}{16}$ inch thick. In default of a copper plate, an iron plate or pipe of the same surface, and not less than $\frac{1}{8}$ inch thick, may be substituted. The ground wire, not smaller than No. 4 (A. W. G.), should be securely soldered across the entire surface of the plate. This plate should then be covered with one or two feet of crushed coke or charcoal, the remainder of the hole being filled in with earth. It is recommended that an additional ground connection be made to the water-main if accessible, thus providing two paths for the escape of the discharge.

The above arrangement is hardly necessary or practicable in the case of line or other subsidiary arresters, and the following ground connection will answer the purpose. A hole is dug two feet in diameter, and deep enough to reach permanently damp earth. A gas-pipe eight or ten feet long with open ends is then driven down, and a solid brass plug is screwed in the upper end, to which the ground wire of the arrester is soldered; the hole is then filled in with coke or charcoal, so that the surface drainage will increase the natural dampness of the earth.

The subject of protection against lightning must be admitted to be somewhat uncertain at the present time. While the general laws and phenomena are the same as those with which we are familiar in connection with artificial electricity, the enormous magnitude and intensity of atmospheric electrical actions introduce

effects which are not yet fully understood. Probably the greatest cause of confusion and disagreement has been the fact that there are so many *different kinds* of atmospheric electrical discharges. Indeed, it almost seems as if no two discharges act the same. This is due to difference of conditions, which a little more knowledge would doubtless correlate and explain. As an example of a phenomenon entirely unlike the ordinary idea of lightning, we may cite the statement of Mr. Wurts: * "I have known circuits to become charged during *perfectly clear weather*, so that the discharges across a single lightning-arrester occurred at the rate of 100 to 140 a minute. It seems to me that the charging of the wire in this case must of necessity be due to conduction from the atmosphere."

* *Trans. Amer. Inst. Elec. Eng.*, vol. xi., p. 392.

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